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CLINOCLASITE

CHARLES PALACHE, *Harvard University*, AND

L. G. BERRY, *Queen's University*,

Kingston, Canada.

ABSTRACT

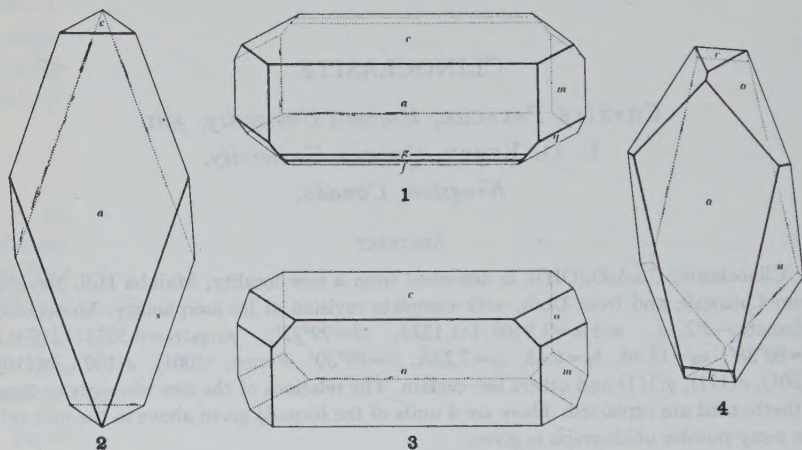
Clinoclasite, $\text{Cu}_3\text{AsO}_4(\text{OH})_3$, is described from a new locality, Majuba Hill, Nevada, from Cornwall, and from Utah, with complete revision of its morphology. Monoclinic; prismatic— $P2_1/a$. $a:b:c=1.9109:1:1.1223$, $\beta=99^\circ22'$; $p_0:q_0:r_0=0.5873:1.1073:1$, $\mu=80^\circ38'$; $a_0=12.36$, $b_0=6.45$, $c_0=7.23\text{\AA}$, $\beta=99^\circ30'$. Forms: $c(001)$, $a(100)$, $m(110)$, $g(201)$, $o(111)$, $q(\bar{1}11)$ and others less certain. The relations of the new elements to those hitherto used are explained. There are 4 units of the formula given above in the unit cell. An x-ray powder photograph is given.

The copper arsenate clinoclasite was first found among the numerous gossan minerals of the copper mines of Cornwall. It was striking in color and in the very symmetrical spherical and cylindrical shapes of the aggregates in which it commonly occurred. Single crystals were rare and the measurements recorded by Brooke (1822) and Phillips (1823) were stated to be approximate only, because of the small size and warped faces of the crystals studied. No better crystals have been found up to the present time, although some of different habit and likewise yielding only approximate measurements were described by Hillebrand and Washington (1888) from Tintic, Utah. All crystallographic data for clinoclasite rest then on imperfect measurements. The mineral remains a rare one, only two or three additional localities having been recorded for it.

Clinoclasite crystals, identified on specimens from Majuba Hill, Nevada, sent to the Harvard Mineralogical Laboratory for examination by Professor V. P. Gianella, proved to be suitable for exact goniometric study. The results of this examination lead to so considerable a revision of the elements, forms and setting of the species that it seems desirable

to place them on record. The relations of the new data to the old will be discussed after the newly won facts are presented.

The Nevada clinoclasite consists in part of slender needles, isolated or loosely grouped on a siliceous matrix,—in part of small rosettes of similar needles grouped in spherical radiations. The needles are so dark a blue as to appear black in reflected light. The rosettes and any bruised crystals show the pearly cleavage and the lovely greenish-blue color so characteristic of the mineral.



FIGS. 1-4.—Clinoclasite crystals. FIG. 1.—Nevada, with forms: $c(001)$, $a(100)$, $m(110)$, $f(302)$, $g(201)$, $q(\bar{1}11)$. FIG. 2.—Cornwall, with forms: $c(001)$, $a(100)$, $s(\bar{5}52)$. FIG. 3.—Utah, with forms: $c(001)$, $a(100)$, $m(110)$, $o(111)$. FIG. 4.—Utah, with forms: $c(001)$, $a(100)$, $k(\bar{4}01)$, $o(111)$, $u(\bar{9}72)$.

Clinoclasite is monoclinic and it was evident that these needles were elongated parallel to the symmetry axis b . There was some difficulty in detaching crystals free from distortion due to the easy gliding transverse to the basal cleavage, but several were obtained practically undisturbed. The crystals were mostly implanted by one end of the b -axis, but occasionally doubly terminated needles could be found. Their size averages 0.1 mm. in diameter by 1 mm. in length.

The b -axis and the orthopinakoid zone were adjusted to the axis of the vertical circle of the goniometer, and all measurements in what follows were made in this position of second permutation with (010) as pole. Calculations of the observed angles followed the method given by Wolfe (1941) for this position.

The crystals proved to be terminated generally by two pairs of excellent faces taken respectively as unit prism $\{110\}^*$ and negative unit prism $\{\bar{1}11\}$. If one pair was missing, it was always the latter. The strongest form in the zone $[010]$ was that to which the perfect cleavage is parallel, $\{001\}$; but scarcely less well developed was a pinakoid in a radial zone with the prism $\{110\}$, hence to be taken as $\{100\}$. Other forms than these were confined to slight striated areas between them, indexed with uncertainty as orthopinakoids $\{301\}$, $\{302\}$, $\{201\}$, and $\{502\}$. The appearance of the crystals is shown in Fig. 1; the measurements are presented on a later page in Table 1 together with those of other clinoclasite crystals. There was no ambiguity in the choice of axes and indices for the main forms as shown in gnomonic projection; the axes so chosen were confirmed by the x -ray study recorded on a later page by Dr. Hurlbut.

While there was good agreement between the position of some of the forms found on the Nevada clinoclasite and the recorded data, the differences were so considerable for others that it was evidently important to measure and compare with these crystals others from Cornwall and Tintic. Search of the collection finally revealed two specimens, one from each locality, which provided crystals of surprisingly good quality.

The Cornish crystals are shown in Fig. 2. They are tiny tablets 0.1–0.25 mm. by 0.1–0.2 mm. which show but three forms, the two pinakoids $\{001\}$ and $\{100\}$ and a steep negative prism $\{\bar{h}kl\}$. The measurements obtained from four of them are contained in Table 1. The two pinakoids gave excellent signals despite their small size and there was no trace of other forms in the zone with them. The faces of the prism, however, were uneven and gave a group of poor signals separated both in ϕ and ρ by several degrees so that the positions given in the table for it are approximations only.

The crystals from the Tintic specimen proved to be the best ones found. They differ from the Nevada crystals but little in general form as shown by Fig. 3. The slender needles are elongated on $[010]$ and have as terminal faces generally two pairs of faces belonging to the unit prism $\{110\}$ and the positive unit prism, $\{111\}$, both of which gave good and consistent position angles. If one pair was lacking, it was the prism $\{110\}$. The measurements of four of these Tintic crystals form the last group of Table 1. There were no indications either on these or on the Cornwall crystals of any faces in the orthodome zone except the two pinakoids.

* Nomenclature of monoclinic prisms follows Federov as modified by Rogers, *Am. Mineral.*, 20, 838 (1935).

TABLE 1. MEASUREMENTS OF CLINOCLASITE CRYSTALS
(010) as pole

(a) Nevada							
	Number of		Qual.	ϕ_2	ρ_2	Range	
	crysts.	faces				ϕ_2	ρ_2
<i>c</i> 001	9	16	fair	80°53'	90°00'	80°19'–81°40'	—
<i>a</i> 100	9	18	good	0 00	90 00	—	—
<i>m</i> 110	9	10	good	0 00	28 02	—	27°55'–28°20'
<i>h</i> 502	1	1	poor	144 05	90 00	—	—
<i>f</i> 302	5	7	poor	127 41	90 00	125 54–128 28	—
<i>g</i> 201	4	6	poor	134 17	90 00	131 22–136 07	—
<i>d</i> 301	1	1	good	27 56	90 00	—	—
<i>o</i> 111	2	44	v. poor	52 40	48 28	52 19–52 55	48 13–48 45
<i>q</i> 111	7	10	good	113 11	44 15	112 31–113 49	44 00–44 35
<i>s</i> 552	1	1	v. poor	140 14	31 20	—	—
(b) Cornwall							
<i>c</i> 001	4	7	good	80 32	90 00	80 26–80 41	—
<i>a</i> 100	4	7	good	0 00	90 00	—	—
<i>s</i> 552?	2	3	v. poor	144 28	33 38	142 22–146 17	33 32–33 50
	2	4	v. poor	148 43	33 40	148 11–149 00	33 10–34 00
(c) Tintic, Utah							
<i>c</i> 001	3	6	v. good	80 31	90 00	80 26–80 36	—
<i>a</i> 100	3	6	v. good	0 00	90 00	—	—
<i>m</i> 110	3	4	good	0 00	28 10	—	28 00–28 18
<i>o</i> 111	3	5	v. good	52 40	48 10	52 08–52 58	48 05–48 25

Examining the data of Table 1, it may be seen that the values marked *good* and *very good* relate in all three localities to the two pinakoids *a* and *c*; and on the Nevada and Utah crystals to the prism {110} and the two prisms {*hkl*} *o* and *q*. The general average of the ϕ_2 angles of {001} is $80^\circ 38' = \mu = 180^\circ - \beta$. After calculating the elements of the Nevada and Utah crystals separately (the Cornwall crystals could not be used because the symbol of the prism {*hkl*} is uncertain) it was concluded that the best treatment was to use the position angles of *o* {111} and *q* {111} in one operation, although these values were derived from sets of crystals from two localities. The results are as follows:—

$$r_2 = 0.9031 \quad a = \frac{1}{p_2 \sin \mu} = 1.9109$$

$$p_2 = 0.5304 \quad c = \frac{1}{r_2 \sin \mu} = 1.1223$$

$$\mu = 80^\circ 38' \quad \beta = 99^\circ 22'$$

From these elements the angle table, Table 2, was calculated.

TABLE 2. ANGLE TABLE FOR CLINOCLASITE
Monoclinic; prismatic

$$a:b:c=1.9109:1:1.1223; \beta=99^\circ 22', r_2:p_2:q_2=0.9031:0.5304:1$$

$$p_0:q_0:r_0=0.5873:1.1073:1; \mu=80^\circ 38', p_0'=0.5953, q_0'=1.1223, x_0'=0.1650$$

	ϕ	ρ	ϕ_2	$\rho_2=B$	C	A
<i>c</i> 001	90°00'	9°22'	80°38'	90°00'	—	80°38'
<i>a</i> 100	90 00	90 00	0 00	90 00	80°38'	—
<i>m</i> 110	27 56½	90 00	0 00	27 56½	85 37½	62 03½
<i>d</i> 301	90 00	62 51½	27 08½	90 00	53 29½	27 08½
<i>f</i> 302	—90 00	36 03	126 03	90 00	45 25	126 03
<i>g</i> 201	—90 00	45 43½	135 43½	90 00	55 05½	135 43½
<i>h</i> 502	—90 00	52 55½	142 55½	90 00	62 17½	142 55½
<i>o</i> 111	34 07	53 35	52 45	48 13½	48 46	63 10
<i>q</i> 111	—20 58½	50 14½	113 17	44 07½	54 06½	105 58½
<i>s</i> 552?	—25 15	72 08	142 56½	30 35½	76 18½	113 57
* <i>k</i> (401)?	—90 00	65 43	155 43	90 00	75 05	155 43
(972)?	—34 38½	78 10	159 46	36 22	83 35	123 48
* <i>u</i> (761)?	—30 43½	82 43½	165 58	31 29½	87 34	120 27

* Doubtful additional forms noted by Berry.

The comparison of measured (average) angles with calculated values shown in Table 3 reveals only a moderately good agreement, but this is perhaps as might be expected from the somewhat meager material upon which the calculated angles are based.

TABLE 3. COMPARISON OF MEASURED (AVERAGE) AND CALCULATED ANGLES

	Measured (aver.)		Calculated	
	ϕ_2	ρ_2	ϕ_2	ρ_2
001	80°38'	90°00'	80°38'	90°00'
110	0 00	28 06	0 00	27 56½
111	52 40	48 10	52 45	48 13½
111	113 11	44 15	113 17	44 07½

X-Ray Crystallography by C. S. Hurlbut, Jr. One of the crystals in which the a and c faces could be easily recognized was used for x -ray study. Rotation and zero- and first-layer line Weissenberg photographs were taken with b [010] the axis of rotation. From the zero-layer Weissenberg photograph the spacings $d_{(100)} = 12.17 \text{ \AA}$ and $d_{(001)} = 7.11 \text{ \AA}$ were determined. A zero-layer Weissenberg photograph was taken with c [001] the axis of rotation, from which $d_{(010)} = 6.42 \text{ \AA}$ was obtained. This corresponds closely to a spacing of $d_{(010)} = 6.40 \text{ \AA}$ obtained from the rotation photograph about b [010]. From calculations made from x -ray data the angle $\mu = 79^\circ 57'$. The value of $\mu = 80^\circ 38'$ obtained from morphological crystal measurements is believed to be the more accurate and was, therefore, used to calculate the absolute lengths of the axes, which are:

$$a_0 = 12.33 \text{ \AA}, b_0 = 6.42 \text{ \AA}, c_0 = 7.21 \text{ \AA}.$$

The ratios of these lengths are:

$$a_0 : b_0 : c_0 = 1.921 : 1 : 1.122.$$

From the criteria

hkl present in all orders.

$h0l$ present only with h even.

$0k0$ present only with k even.

The space group was determined to be $P2_1/a$.

Optical Properties. Dr. Hurlbut re-determined the optical properties of clinoclasite from Majuba Hill and from Tintic, Utah. He confirmed the orientation given in Larsen's tables but revised the refractive index data as follows:—

$$\alpha = 1.756, \beta = 1.874, \gamma = 1.896, 2V = 50^\circ.$$

In order to bring out the relation of the new data on clinoclasite to the morphology as recorded in the literature, there is presented in Table 4 a tabulation taken from *Goldschmidt's Winkeltabellen* for "Abichite" (an old name for clinoclasite) transformed to the position of second permutation as used in this paper.

TABLE 4. ANGLE TABLE FOR "ABICHITE," GOLDSCHMIDT

$r_2 = 0.2633$	$p_2 = 0.5317$	$\mu = 80^\circ 30'$
	ϕ_2	ρ_2
c 001	$80^\circ 30'$	$90^\circ 00'$
a 100	0 00	90 00
m 110	0 00	28 00
r 101	24 18	90 00
s 302	161 00	90 00
t 111	151 59	28 56
p 113	117 $15\frac{1}{2}$	41 14

On first inspection there is great resemblance between this table and the corresponding angles of Tables 1 and 2. There is essential identity as regards the mutual attitude of the pinakoids, the angle of the prism $\{110\}$, and the value of p_2 ($p_2 = \tan \rho_{110}$). But beyond this the resemblance is not so close. r_2 of Table 4 is approximately one-third of r_2 of Table 2 (0.3010). This is equivalent to considering the new value of c as one-third of the old one; otherwise stated, the form $p\{\bar{1}13\}$ becomes $\{\bar{1}11\}$ in the new position, an identity which was at first accepted in this study.

		ϕ_2	ρ_2
Table 4	$p \ \bar{1}13$	$117^\circ 15\frac{1}{2}'$	$41^\circ 14'$
Table 2	$q \ \bar{1}11$	$113 \ 17$	$44 \ 07\frac{1}{2}$

But this apparent resemblance is fallacious. Examination of the figures of clinoclasite in *Dana* or in *Goldschmidt's Atlas*, Vol. 5, Plate 16, shows that on every one $m\{110\}$ is a dominant form, the other two principal forms being $c\{001\}$ and $s\{\bar{3}02\}$, the latter often with other lettering. More striking is the absence on most of the figures of $a\{100\}$, which on all our crystals is a dominant form. It is to be remembered that the axial ratio of Phillips, used also by *Dana* and *Goldschmidt*, was calculated from approximate measurements on crystals from Cornwall. His position was probably chosen to enable a value for the ratio of a to c to be calculated from the faces of the orthopinakoid zone, since the prism $\{hkl\}$ was probably difficult to measure exactly and could thus be made the prism $\{110\}$. If *Dana's* Fig. 2 be compared to Fig. 2 on a preceding page, it will be seen that they are essentially identical, but *Dana's* figure must be turned front for back and then tilted forward until the face s is vertical for the identity to appear fully. Our morphological study and the x -ray analysis prove that our position for a crystal of this type is the correct one.

The figures of Tintic crystals shown in *Dana* were drawn by Washington (1888) when a student under Penfield at Yale. He followed Phillip's setting, as was quite natural, as he states that his crystals did not admit of accurate measurement. His figures are comparable to our Fig. 3 except that the orthopinakoid $s\{h0l\}$ should be made the front pinakoid as just explained, and his prism $\{110\}$ would then become a negative prism $\{\bar{h}kl\}$. Furthermore, it is to be noted with regard to the two forms $t\{\bar{1}11\}$ and $p\{\bar{1}13\}$ of Table 4, which were established by Washington, that the faces were poor and that the calculation of the symbol, at least for p , is in error. Washington's measured angles, plotted stereographically on Phillips' axes, do not fall within many degrees of the position of $\{\bar{1}13\}$. They yield rather a symbol near $\{\bar{5}.3.10\}$; and all of the angles calculated for the new form p were wrong, corrected long ago by *Dana* in the *System*. In short, the terminal face which in Table 3 seemed to be equiva-

lent to the new $\{\bar{1}11\}$ has no existence in reality. The form t may have been the equivalent of our form $\{\bar{5}52\}$, but the one angle given for it is insufficient to determine its nature.

When Phillip's angles are plotted stereographically with his axes and then subjected to the rotation described above as necessary to bring them to our position, the angles of the new positions can be used to calculate the transformed symbols. They are as follows:—

Phillips	Palache
<i>c</i> 001	<i>c</i> 001
<i>s</i> 302	<i>a</i> 100
<i>a</i> 100	501
<i>r</i> 101	201
<i>m</i> 110	551

But our measurement of the prism $\{\bar{h}kl\}$ on Cornish crystals seemingly equivalent to the $\{110\}$ of Phillips is much nearer to $\{\bar{5}52\}$. It is clear that there has been some mistake in angles, probably those of the poor prism $\{\bar{h}kl\}$ form. It seems an odd chance that Phillips' angle c to s , which is $80^{\circ}30'$, should be identical with the angle a to c . This, too, might well have led to error or confusion. It was thought that this transposition could be expressed in a transformation formula. A very complex formula was obtained which, however, failed for two of the five forms and the attempt was abandoned in the certainty that there is a concealed error in Phillips' original measurements.

Our conclusion, then, is that the current crystallographic data for the mineral clinoclasite are erroneous and that the published figures are incorrect. It is hoped that the present study will adequately replace both data and illustrations.

SUPPLEMENTARY OBSERVATIONS

L. G. BERRY

In the course of an x -ray investigation of clinoclasite and other mineral phosphates, arsenates, and vanadates of the type $A_3XO_4(OH)_3$, it was learned that Professor Palache had prepared the foregoing account of his observations on clinoclasite. Since the writer's observations on clinoclasite confirm and amplify the work done at Harvard University they are included in the present paper. These additional observations were made on four specimens, three of which were kindly loaned from the Royal Ontario Museum by Professor V. B. Meen:

1. Clinoclasite (Queen's University collection), St. Day, Cornwall, England; dark greenish-blue crystals aggregated in diverging groups.

2. Clinoclasite (Royal Ontario Museum, M/8000, Montgomery collection), Tintic District, Utah; single crystals $\frac{1}{2}$ mm. long on quartz and radiating aggregates of crystals up to 3 mm. long.

3. Clinoclasite (ROM, M/11801), Bullion Beck Mine, Tintic District, Utah; nearly spherical aggregate of radiating crystals $1\frac{1}{4}$ inches in diameter.

4. Clinoclasite (ROM, M/12644), Wheal Gorland, Cornwall, England; radiating aggregates of fine crystals up to 1 cm. in diameter.

Professor M. A. Peacock, University of Toronto, was kind enough to transmit these results to the Harvard Mineralogical Laboratory.

Geometrical crystallography. Clinoclasite from Utah (material 2) offered the only chance of good goniometric measurements. It consists in part of small isolated crystals about $\frac{1}{2}$ mm. long perched on quartz crystals or on a massive quartz matrix. Five crystals were chosen for goniometric measurement (Table 5); four were adjusted on $c[001]$ and one on $b[010]$.

TABLE 5. CLINOCLASITE: CRYSTAL MEASUREMENTS

	Number of		Quality	Average		Range	
	crys- tals	faces		ϕ	ρ	ϕ	ρ
<i>c</i> (001)	3	3	good	90°00'	9°26'	—	9°21'– 9°32'
<i>a</i> (100)	3	6	good	90 00	90 00	—	—
<i>k</i> ($\bar{4}$ 01)	2	2	poor	–90 00	63 34	—	63 26–63 41
<i>g</i> (201)	1	1	poor	–90 00	48 30	—	—
<i>o</i> (111)	3	6	fair	34 31	53 34	34°00'– 35°25'	52 58–54 07
<i>u</i> {	(972)	2	v. poor	–35 05	78 27	–33 07– 37 40	76 43–82 04
	($\bar{7}$ 61)	1	v. poor	–31 01	82 53	–29 42– 32 21	82 50–82 57
				ϕ_2	ρ_2	ϕ_2	ρ_2
<i>c</i> (001)	1	1	good	80°28'	90°00'	—	—
<i>a</i> (100)	1	2	good	0 00	90 00	—	—
<i>k</i> ($\bar{4}$ 01)	1	1	poor	155 34	90 00	—	—
<i>o</i> (111)	1	1	poor	52 29	47 30	—	—
<i>u</i> ($\bar{7}$ 61)	1	2	v. poor	162 24	32 25	162°03'–162°46'	27°39'–37°11'

These crystals (Fig. 4) proved to be somewhat similar to the Cornwall crystal (Fig. 2), elongated parallel to the vertical axis with the pinakoid $a(100)$ as the most prominent form. The crystals are generally terminated by the basal pinakoid $c(001)$, the unit positive prism $o(111)$, and a steep negative prism $u(\bar{9}72)$ or ($\bar{7}61$), in a similar general position to $s(\bar{5}52)$ (Fig. 2). Other forms are confined to a striated zone between $c(001)$ and $a(\bar{1}00)$ indexed with uncertainty as $g(\bar{2}01)$ and $k(\bar{4}01)$.

The faces of u are very uneven, giving a large number of poor signals spread over several degrees in ϕ and ρ . The values given in the table for this form represent the center of the group of signals; the indices given are uncertain.

A comparison of the measured (average) and calculated angles (from Palache's geometrical elements) for the forms observed here is given in Table 6. The measured angles for the forms $c(001)$, $a(100)$, and $o(111)$ compare closely with the calculated angles. The comparison is poor in the case of $u(972)$ or $(\bar{7}61)$, $g(\bar{2}01)$, and $k(\bar{4}01)$, which is to be expected from the poor quality of those doubtful forms.

TABLE 6. CLINOCLASITE: COMPARISON OF MEASURED AND CALCULATED ANGLES

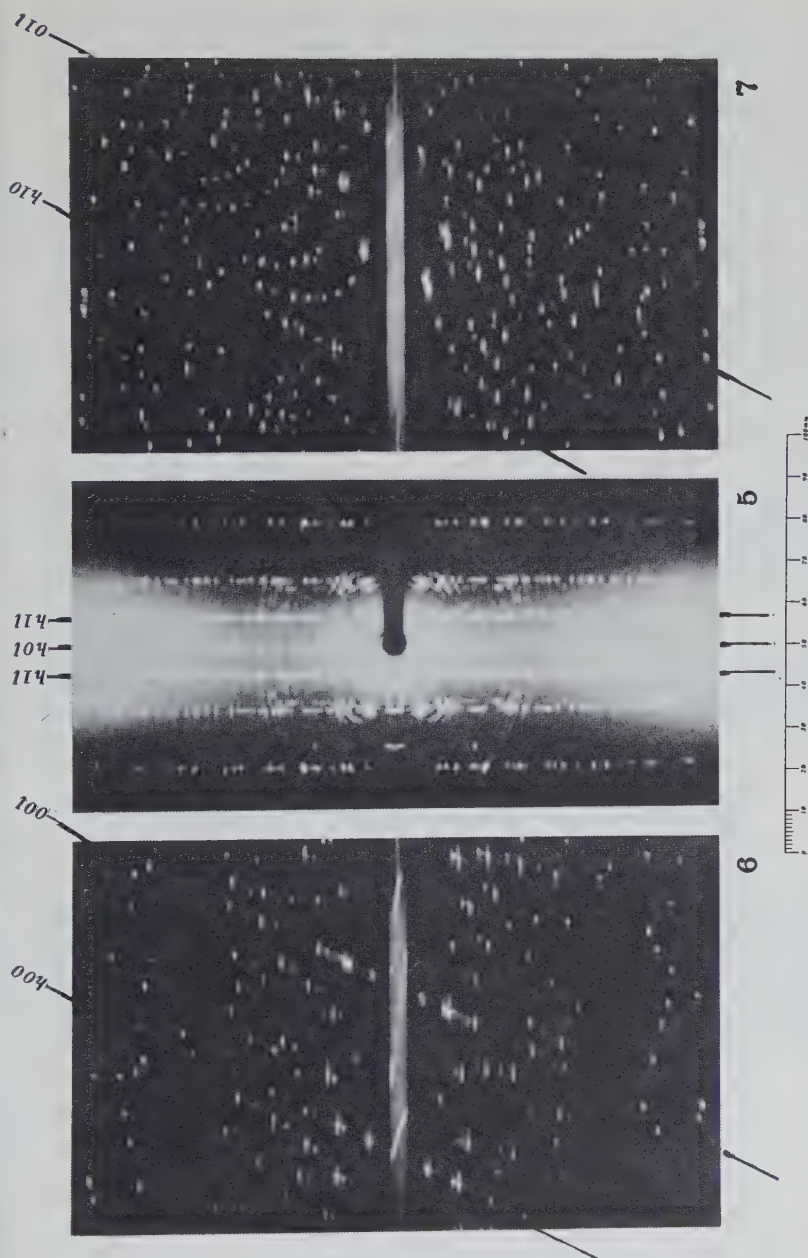
	Measured (average)		Calculated	
	ϕ	ρ	ϕ	ρ
c (001)	90°00'	9°26'	90°00'	9°22'
k ($\bar{4}01$)	-90 00	63 34	-90 00	65 43
g (201)	-90 00	48 30	-90 00	45 43½
o (111)	34 31	53 34	34 07	53 35
u { (972)	-35 05	78 27	-34 38½	78 10
($\bar{7}61$)	-31 01	82 53	-30 43½	82 43½
	ϕ_2	ρ_2	ϕ_2	ρ_2
c (001)	80°28'	90°00'	80°38'	90°00'
k ($\bar{4}01$)	155 34	90 00	155 43	90 00
o (111)	52 29	47 30	52 45	48 13½
u ($\bar{7}61$)	162 24	32 25	165 58	31 29½

X-ray crystallography. Cleavage fragments of clinoclasite suitable for single crystal x-ray measurements were readily obtained from material 1 (Cornwall). Rotation, zero, and first-layer Weissenberg photographs about $b[010]$ (Figs. 5-7) lead to a monoclinic lattice with dimensions:

$$b = 6.45 \pm 0.02, d(100) = 12.19 \pm 0.04, d(001) = 7.13 \pm 0.02 \text{ kX}$$

and axial angle $ac = 80^\circ 30' \pm 15'$. A zero-layer Weissenberg photograph about the normal to the cleavage $c(001)$ gave $d(010) = 6.43 \text{ kX}$. The measured spacings together with the axial angle give the absolute cell dimensions:

$$a = 12.36, b = 6.45, c = 7.23 \text{ kX}; \beta = 99^\circ 30'.$$



FIGS. 5-7.—Clinoclase, Cornwall (material 1); single crystal x-ray photographs with unfiltered Cu-radiation; camera radius $360/4\pi$ mm. The scale gives millimeters or degrees of θ . FIG. 5.—Rotation about $[010]$. FIG. 6.—Weissenberg resolution of the layer ($h0l$). FIG. 7.—Weissenberg resolution of the layer ($h1l$).

The observed diffractions conform to the conditions: (hkl) present in all orders, $(0kl)$ present in all orders, $(hk0)$ present in all orders, $(h0l)$ present only with $h=2n$, $(0k0)$ present only with $k=2n$; these criteria are characteristic of the single space-group, $C_{2h}^2 - P2_1/a$.

Rotation and zero-layer Weissenberg photographs of one crystal from material 2 (Utah), rotated about $b[010]$, give the following lattice dimensions:

$$b=6.45 \pm 0.02, d(100)=12.20 \pm 0.03, d(001)=7.14 \pm 0.02 \text{ kX}$$

axial angle $ac=80^\circ 35' \pm 10'$, and absolute cell dimensions:

$$a=12.37, b=6.45, c=7.24 \text{ kX}; \beta=99^\circ 25'$$

in close agreement with the measurements on the Cornwall clinoclasite given above.

These determinations of the cell dimensions of clinoclasite from Cornwall and Utah agree closely with the results obtained by Hurlbut on clinoclasite from Nevada:

$$a=12.33, b=6.42, c=7.21 \text{ \AA}; \beta=99^\circ 22'.$$

The structural axial ratios also compare closely with the geometrical ratio given by Palache:

$$\begin{aligned} a:b:c &= 1.916 : 1 : 1.121, \beta = 99^\circ 30' \text{ (Berry, x-ray, Cornwall)} \\ a:b:c &= 1.917 : 1 : 1.122, \beta = 99^\circ 25' \text{ (Berry, x-ray, Utah)} \\ a:b:c &= 1.921 : 1 : 1.122, \beta = 100^\circ 03' \text{ (Hurlbut, x-ray, Nevada)} \\ a:b:c &= 1.9109 : 1 : 1.1223, \beta = 99^\circ 22' \text{ (Palache, goniometer)} \end{aligned}$$

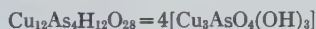
Composition and cell content. The cell dimensions of clinoclasite combined with the highest measured specific gravity, 4.38 (Hillebrand and Washington, 1888), give the molecular weight of the unit cell contents, $M=1509$. In Table 7 this value has been used to obtain the atomic contents of the unit cell from six of the available analyses of clinoclasite.

TABLE 7. CLINOCLASITE: ANALYSES AND CELL CONTENT
 $M=1509$

	1	2	3	4	5	6	A	B
CuO	62.80	60.00	61.68	62.47	62.34	62.72	62.00	62.71
Fe ₂ O ₃	0.49	0.39	n.d.	—	0.12	—	0.17	—
CaO	—	0.50	—	—	ZnO 0.06	—	0.08	—
As ₂ O ₅	27.08	29.71	29.36	30.98	29.59	30.08	29.47	30.19
P ₂ O ₅	1.50	0.64	—	—	0.05	—	0.36	—
H ₂ O	7.57	7.64	7.31	6.62	7.73	(7.20)	7.35	7.10
	99.44	100.00 ¹	98.35	100.07	99.95 ²	100.00	99.43	100.00
Cu	11.97	11.51	11.89	11.84	11.83	11.89	11.88	12.00
Fe	0.10	0.08	—	—	0.02	—		
Ca	—	0.13	—	—	Zn 0.01	—		
As	3.58	3.95	3.92	4.06	3.90	3.95	3.97	4.00
P	0.32	0.14	—	—	0.02	—		
H	12.76	12.94	12.44	11.08	12.98	12.06	12.38	12.00
O	28.25	28.44	27.91	27.53	28.16	27.79	28.01	28.00

1. Cornwall; anal. Damour (1845). 2. Cornwall; anal. Rammelsberg (1846); ¹incl. SiO₂ 1.12. 3. Mammoth Mine, Tintic District, Utah; anal. Pearce (1886). 4. Anal. Coloriano (1886). 5. Mammoth Mine, Tintic District, Utah; anal. Hillebrand (Hillebrand and Washington, 1888); ²incl. SiO₂ 0.06. 6. Anal. Church (1895). A. Average. B. Ideal composition and cell content for 4[Cu₃AsO₄(OH)₃].

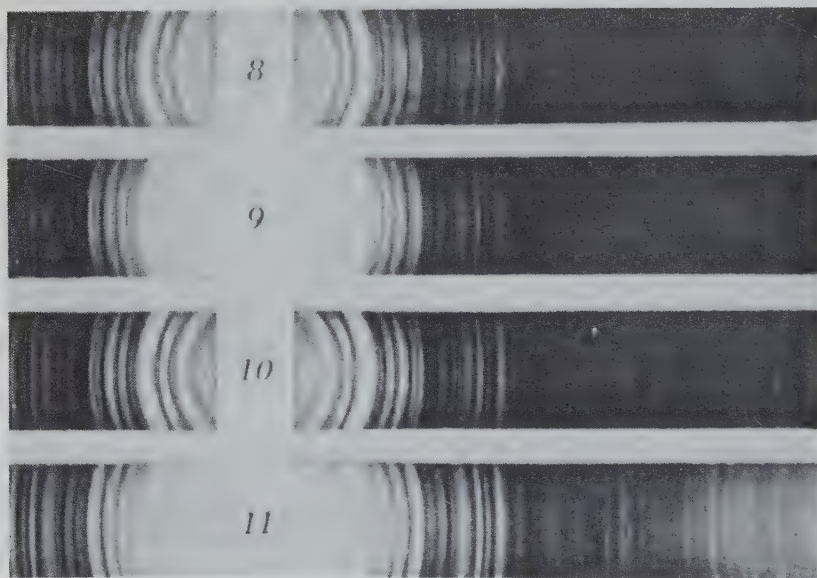
The values obtained clearly indicate the structural formula:



and the average values (A) approach closely the ideal values (B) for this structural formula. This unit cell content gives the calculated specific gravity 4.42, in good agreement with the measured value. This affords complete confirmation of the generally accepted formula of clinoclasite.

X-ray powder photograph. Clinoclasite from each of the four materials

listed above gave identical *x*-ray powder patterns (Fig. 8–11). The measured spacings and estimated intensities for Cu-radiation are listed in Table 8 with the indices and calculated spacings of the reflecting planes. Card number II-791 of the A. S. T. M. *X*-ray Diffraction Data Cards



FIGS. 8–11.—Clinoclasite: *x*-ray powder photographs with Cu-radiation (Ni-filter); camera radius $360/4\pi$ mm. FIG. 8.—St. Day, Cornwall (material 1). FIG. 9.—Tintic District, Utah (material 2). FIG. 10.—Bullion Beck Mine, Tintic District, Utah (material 3). FIG. 11.—Wheal Gorland, Cornwall (material 4). Actual size.

gives a pattern for clinoclase, Wheal Gorland, Cornwall, taken with Cu-radiation, Al-window (BM = British Museum), which agrees substantially with ours. The three strongest lines of the BM pattern are 3.63 (1.0), 3.14 (0.8), 2.05 (0.7) as compared to our 3.55 (10), 3.13 (8), 4.3 (6).

TABLE 8. CLINOCLASITE— $\text{Cu}_3\text{AsO}_4(\text{OH})_3$: X-RAY POWDER PHOTOGRAPH
Monoclinic, $P2_1/a$; $a=12.36$, $b=6.45$, $c=7.23$ kX, $\beta=99^\circ30'$; $Z=4$

$I(\text{Cu})$	$\theta(\text{Cu})$	$d(\text{meas.})$	(hkl)	$d(\text{calc.})$	$I(\text{Cu})$	$\theta(\text{Cu})$	$d(\text{meas.})$	(hkl)	$d(\text{calc.})$
3	6.0	7.55	(001)	7.13 kX				(402)	2.148 kX
3	7.0	6.3	(200)	6.10	3	21.0	2.14	(222)	2.147
1	9.4	4.7	($\bar{1}$ 11)	4.63				(113)	2.136
(3) 6	10.4	4.3	(201)	4.30	4	21.5	2.10	(203)	2.100
			(111)	4.29				(313)	2.094
$\frac{1}{2}$	11.1	3.99	(211)	3.98				(031)	2.058
(1) 10	12.5	3.55	(211)	3.57				(421)	2.047
			(002)	3.56	5	22.0	2.05	(131)	2.046
			($\bar{1}$ 12)	3.13				($\bar{6}$ 01)	2.045
(2) 8	14.2	3.13	(012)	3.12				(403)	2.045
			(120)	3.12				(412)	2.038
			($\bar{4}$ 01)	2.99	$\frac{1}{2}$	23.0	1.967	(231)	1.979
3	14.9	2.99	(212)	2.96				(322)	1.968
4	15.5	2.88	(121)	2.90	1	23.7	1.912	($\bar{6}$ 02)	1.906
			(202)	2.88				(132)	1.844
3	15.7	2.84	(220)	2.85	2	24.7	1.839	(032)	1.841
			(121)	2.81				(313)	1.839
1	16.1	2.77	(410)	2.76				(512)	1.799
3	16.8	2.66	($\bar{3}$ 12)	2.67	2	25.4	1.792	(204)	1.792
			(401)	2.65				(422)	1.787
4	17.7	2.53	($\bar{4}$ 02)	2.53	3	26.6	1.717	(014)	1.718
			(320)	2.53				($\bar{6}$ 03)	1.688
4	18.0	2.49	(321)	2.46	2	27.1	1.687	(710)	1.681
			(411)	2.45				(314)	1.681
			($\bar{1}$ 22)	2.40				(413)	1.680
3	18.8	2.38	(022)	2.39				($\bar{6}$ 22)	1.641
			(003)	2.38	2	27.9	1.643	(204)	1.640
			(312)	2.32				($\bar{4}$ 32)	1.639
			(222)	2.31	2	28.5	1.611	(040)	1.612
5	19.5	2.30	(321)	2.31				($\bar{4}$ 14)	1.610
			(122)	2.30				(801)	1.543
			($\bar{1}$ 13)	2.26	4	29.9	1.542	(333)	1.543
4	20.1	2.24	(013)	2.23					
$I(\text{Cu})$	$\theta(\text{Cu})$	$d(\text{meas.})$	$I(\text{Cu})$	$\theta(\text{Cu})$	$d(\text{meas.})$	$I(\text{Cu})$	$\theta(\text{Cu})$	$d(\text{meas.})$	
3	31.0	1.492	$\frac{1}{2}$	40.9	1.174	1	57.1	.9155	
1	31.6	1.467	2	41.9	1.151	$\frac{1}{2}$	59.4	.8930	
3	32.6	1.427	1	42.8	1.131	1	60.8	.8806	
3	32.9	1.415	2	43.4	1.119	1	62.8	.8642	
1	33.6	1.389	$\frac{1}{2}$	44.7	1.093	1	64.7	.8502	
1	33.8	1.382	2	47.2	1.048	$\frac{1}{2}$	65.9	.8421	
1	34.7	1.350	2	48.8	1.022	$\frac{1}{2}$	69.4	.8212	
1	39.1	1.219	1	51.5	.982	1	74.5	.7977	
$\frac{1}{2}$	39.8	1.201	$\frac{1}{2}$	53.3	.959	$\frac{1}{2}$	81.6	.7770	
2	40.5	1.184							

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CLINOCLASITE FROM MAJUBA HILL, NEVADA

VINCENT P. GIANELLA, *University of Nevada, Reno, Nevada.*

Clinoclasite, a rare copper arsenate, has been known to be present at Majuba Hill for many years,¹ but good crystals were rare. During development work, in the fall of 1941, Mr. Charles Yetter² found some dark blue-green crystals which he submitted to the writer for determination. The mineral proved to be exceptionally well crystallized clinoclasite. Because of some unusual features of this occurrence samples were sent to Professor Charles Palache for further study.

Majuba Hill (erroneously designated Majuba Mountain, on the U. S. Geol. Survey Lovelock quadrangle) rises to an elevation of 6,886 feet in the Antelope Mountains, a northern continuation of the Trinity Range in Pershing County, Nevada. It lies in sec. 2, T. 32 N., R. 31 E. Mount Diablo base and meridian. The mountain consists of a rhyolite plug intruded into Triassic (?) sediments.³ The sediments are dominantly slate, phyllite, hornfels, and quartzite. The sediments strike northeast and dip steeply to the northwest. The plug is roughly oval in outline with a length of about one mile and a width of about 0.8 mile. The longer axis, and many of the larger associated dikes, trend parallel to the strike of the sediments. In many places the rhyolite is brecciated with the fragments set in a matrix of finely-crystallized black tourmaline. Thin veinlets of tourmaline, with minor amounts of fluorite and quartz, are abundant in some parts of the rhyolite and commonly the sanidine phenocrysts have been entirely replaced by an aggregate of fine needles of tourmaline and slender doubly-terminated quartz crystals.

In 1916 copper ore was discovered on a fault striking N. 50° W. and dipping 60° southwest. This ore body is reached through an adit entering the south side of the mountain at an elevation of 6,250 feet. The primary ore consists largely of chalcopyrite, arsenopyrite, and pyrite, with minor amounts of cassiterite. There is also much cuprite and some chalcotrichite, chalcocite, native silver, azurite, malachite, bornite, and many other secondary minerals. In driving the adit farther into the mountain, a shoot of tin ore was discovered in 1917 about 200 feet beyond the copper ore body. The tin ore is in the hanging wall but a short distance from the fault. The ore is composed of cassiterite⁴ in a matrix of doubly-terminated

¹ Gianella, V. P., Nevada's Common Minerals: *University of Nevada, Bull.* 35, no. 6, p. 95 (1941).

² Engineer for The Freeport Texas Company.

³ Smith, Ward C., and Gianella, V. P., Tin deposit at Majuba Hill, Pershing County, Nevada: *U. S. Geol. Survey, Bull.*, 931-C (1942).

⁴ Knopf, Adolph, *Mineral Resources* (1917), Pt. I, pp. 64-65 (1918). Also, *Mineral Resources* (1918), Pt. I, pp. 22-23 (1919).

quartz crystals, black tourmaline, and iron oxides. Some scorodite is present and, in places, numerous fine crystals of olivenite. No ore was extracted from this ore body at that time. In the fall of 1941 the Freeport Texas Company took over the property and during their exploration a raise was driven along the fault to further explore the tin-bearing area. The excellent crystals of clinoclasite were discovered a short distance above the tin stope. The clinoclasite is associated with malachite, azurite, olivenite, and hydrated oxides of iron. The clinoclasite occurs in radiating crystals up to six millimeters in length and also as tufts of small crystals and as drusy incrustations in fractures in the tourmalinized rhyolite. Some of these fractures are coated with iron oxide upon which are deposited small crystals of olivenite and clinoclasite. Clinoclasite and other copper arsenates are found in the slightly oxidized primary ore. The arsenates are apparently derived from the primary copper minerals and arsenopyrite through weathering and carried downward by meteoric waters penetrating the faulted and brecciated rhyolite.

The writer wishes to acknowledge his appreciation of the Freeport Texas Company for accommodations while visiting the property and to its employees for many courtesies they extended.

LINEAR ANALYSIS OF A MEDIUM-GRAINED GRANITE¹

FELIX CHAYES²

ABSTRACT

The design and results of an experimental evaluation of the precision of linear analysis are described. It is shown that no systematic error is introduced by duplicate or multiple measurements of the same grain, providing the traverses are evenly spaced throughout. The precision error, whether of a single linear analysis or of a mean based on a group of such analyses, varies directly with the traverse interval. The mean of a large number of linear analyses will not differ from a true Rosiwal analysis of the same group of slides.

Numerical statements of these conclusions are given for the Woodstock, Maryland, granite as analyzed by the writer on the Hurlbut and Wentworth-Hunt micrometers. The precision error of a single analysis is small in comparison to differences between thin sections; in this case it may be neglected. It is shown by comparison of Hurlbut- and Wentworth-stage results that the precision of the two instruments is of the same order.

INTRODUCTION

In the linear traverse method as described by Rosiwal (1) the unit of the sample is the individual grain, and this unit has been retained by Lincoln and Reitz (2) in their well-known investigation of the precision of the method. The continual improvement of measuring devices and the increasing reliance of petrographers on thin sections rather than polished slabs has greatly reduced the practical importance of the single grain. Partly from convenience and partly from necessity, the thin section has replaced the grain as the sample unit; information concerning grain size is not obtained in routine operation of any of the instruments used for this work. Wentworth's original suggestion (3) that the traversing interval be standardized at 1 mm. regardless of grain size has never been criticized, and has apparently found such favor that in their recent papers neither Larsen and Miller (4)* nor Postel and Lufkin (5) considered a theoretical discussion of traverse interval necessary. Yet since the Wentworth procedure often requires duplicate or multiple measurements of the same grain, it does not meet the standard set up by Rosiwal and is specifically excluded from the category of methods that might be justified by the Lincoln-Reitz analysis. Petrologists nevertheless continue to refer to their analyses as Rosiwal analyses and, if they are pressed for some rationalization of the procedure, many of them will cite the excellent work of Lincoln and Reitz.

In connection with the standardization of certain physical testing procedures the writer was recently called upon for an estimate of the miner-

¹ Published by permission of the Director, Bureau of Mines, U. S. Dept. of the Interior.

² Petrographer, Bureau of Mines, College Park, Maryland.

* This paper contains a full bibliography.

alogical uniformity of prepared surfaces of the Woodstock, Maryland, granite. The samples were in the form of AX diamond-drill core, and the test specimens were prepared by sawing the core into appropriate lengths. The rock was to be used as one of several provisional standards; multiple tests were to be run on it, and the spread of these results was to be considered "instrumental variation." It was obvious that this procedure would be satisfactory for tests involving the bulk composition of each specimen; but several of the tests concern properties of only the end-surfaces of the specimens, and it was not entirely clear that these small surfaces would be of sufficiently uniform composition. Some estimate of the mineralogical differences to be expected from surface to surface was desired, and it seemed that this could best be made with thin sections, since the areas of the test surfaces were of about the same order as those of standard thin sections.

A linear analysis is subject to uncertainty from three principal sources; the precision or reproducibility of each individual measurement, the variability of thin sections, and the accuracy of the final result. Most studies of the problem have attempted to treat the third factor by comparisons of mode and norm. A few have been concerned with the first factor, but there seem to be no recorded studies of the second. By and large, the petrologist may be somewhat concerned with his individual measurements, but his strongest interest is in the accuracy of the final result, judged in relation to external (usually chemical) standards, and the variability of thin sections usually has nothing but a nuisance value for him.

The orientation of the present study is very different from that of normal geological work. It is not concerned with accuracy but is primarily interested in thin-section variability (or sample variance), and this variability can be properly interpreted only if the error of individual measurements is either known or reduced sufficiently so that it may be neglected.

The immediate problem in our laboratory was to determine both the precision with which a Wentworth (6) stage could be operated and the sample variance of areas of a size that could be measured on that stage. The simplest and best test of precision consists simply in remeasuring the same slide or area a large number of times and then comparing the results. Although there may be errors in identification and manipulation, the principal source of uncertainty is in the traverse path, and any satisfactory test of precision must include this factor. What is needed is a single area in which the operator may perform successive analyses of equal length over many different traverse paths. The Wentworth instrument as marketed does not provide for the systematic spacing of trav-

erses, and even with a piece of millimeter graph paper glued to the stage the smallest distance between adjacent traverses is 0.5 mm., so that if one is attempting to gauge the precision of analyses made with a 1-mm. traverse interval, only two analyses may be obtained from each slide. Consequently no satisfactory direct test of precision on the Wentworth stage was developed.

The Federal Geological Survey's Hurlbut (7) stage, made available to the writer through the courtesy of Dr. C. S. Ross, has been equipped by the Survey machine shop with a Spencer mechanical stage calibrated in millimeters, with a vernier reading in tenths of a millimeter. A direct single-slide test of precision was made on this stage.

On each of eleven thin sections analyses were then made with the Wentworth and Hurlbut stages, the measurements in each case being confined to a $\frac{3}{4}$ inch diameter circle drawn on the slide. From this information numerical estimates of the sample variance were obtained, and the results showed that the precision error of the Wentworth instrument, like that of the Hurlbut stage, could easily be reduced to negligible size.

A great many shorter experiments confirm the conclusions based on these major tests. Some of these are described below, but detailed accounts of most have been omitted, since often they are not germane to the main outlines of the discussion. In particular, several attempts to determine precision directly on the Wentworth stage were made before the indirect procedure described below was adopted. A good deal of information concerning the effect of orientation has been accumulated, but this is strictly a question of accuracy rather than precision or sample variance, and it is planned to treat it separately in a later paper. There is some evidence that a slight discrepancy in means may be introduced by illumination differences, so that the quartz and feldspar values determined on the Wentworth stage do not check as closely as might be desired with those obtained on the Hurlbut instrument. This effect is very persistent but so small that its influence on mean values could not be exactly determined without an amount of work out of all proportion to its importance; in any case, it affects neither sample variance nor precision.

Finally, the effect of the traverse area on the variance has been partly investigated. Much work remains to be done along these lines, however, and here it need only be said that unless otherwise stated the sample variances described below are valid only for areas of about 0.44 square inch (actually circles $\frac{3}{4}$ inch in diameter).

The argument in this paper is largely of the elementary sort that is almost self-evident once its terms are defined. A few terms that may be

unfamiliar to some readers recur throughout, and in order to facilitate reference, definitions and symbols are presented in a separate section.

TERMS AND SYMBOLS

The terms and symbols used in this paper are those required for almost all treatments of the precision of measurements. Some of them are common words that are given precise definitions in elementary statistics while a few have no significance except in that subject. The latter are defined first.

Variance is the mean square of the deviations about their mean. It is given by:

$$V = \frac{\sum(X - \bar{x})^2}{n - 1} \quad (1)$$

where \bar{x} is the mean of $X_1, X_2, X_3 \dots X_n$ measurements.

The *standard deviation* is the square root of the variance;

$$s = \sqrt{\frac{\sum(X - \bar{x})^2}{n - 1}} = \sqrt{V}. \quad (2)$$

The *standard error or standard deviation of the mean* is,

$$s_{\bar{x}} = \sqrt{\frac{\sum(X - \bar{x})^2}{n(n - 1)}} = \frac{s}{\sqrt{n}}. \quad (3)$$

The properties of s as a measure of variation are well-known. For normally distributed measurements of a given quantity, the range $\bar{x} \pm s$ includes about 65 per cent of all values if s and \bar{x} are close approximations of the true population parameters, and on the same condition the range $\bar{x} \pm 2s$ includes 95 per cent of all similar measurements.

The standard error or error of the mean is used here for determining the number of analyses which would be required to achieve some stated precision of the mean. Its application is described below, where this question is discussed.

Variability and *variation* are used to describe a condition quantitatively expressed in terms of variance, standard deviation or standard error. *Precision* (or *precision error*) is a measure of the reproducibility of a particular measurement or group of measurements. In the former case it is here stated quantitatively as a standard deviation, in the latter as a standard error. It has nothing to do, directly, with accuracy, and the question of the accuracy of linear analysis is not touched upon in this paper.

DIRECT SINGLE-SLIDE PRECISION TEST ON THE HURLBUT STAGE

On a typical thin section of Woodstock granite traverses were made at 0.1-mm. intervals from one edge of the slide to the other. The tallies

on the recording dials were copied at the end of each traverse in tabular form, and the table was differenced, yielding 173 separate traverses. These were next copied onto numbered cards and the cards arranged to give the following sets of analyses:

9 analyses with traversing interval of 0.9 mm.

10	"	"	"	"	"	1.0	"
11	"	"	"	"	"	1.1	"
20	"	"	"	"	"	2.0	"
40	"	"	"	"	"	4.0	"

For each suite of analyses the average and standard deviation were computed for each of four constituents. Results are shown in Tables 1 and 2.

TABLE 1. MEANS OF MULTIPLE ANALYSES OF THE SAME SLIDE
WITH DIFFERING TRAVERSE INTERVALS

Traverse interval, mm.	Number of analyses	Mean values, per cent			
		Quartz	Feldspar	Mica	Epidote
0.9	9	27.28	62.57	9.15	1.27
1.0	10	27.19	62.45	9.09	1.27
1.1	11	27.01	62.68	9.04	1.27
2.0	20	27.03	62.34	9.36	1.27
4.0	40	26.94	62.70	9.11	1.25

TABLE 2. STANDARD DEVIATIONS FOR GROUPS WHOSE MEANS
ARE SHOWN IN TABLE 1

Traverse interval, mm.	Number of analyses	Standard deviation of a single analysis (per cent of whole)			
		Quartz	Feldspar	Mica	Epidote
0.9	9	0.80	1.43	1.24	0.48
1.0	10	1.34	1.13	0.93	0.53
1.1	11	0.67	2.81	0.88	0.43
2.0	20	2.63	3.56	1.78	0.65
4.0	40	4.10	4.47	2.06	0.99

The first three rows in these tables, and particularly in Table 2, can scarcely compare in reliability with the last two, being based only on small groups. It is impossible to repair this deficiency experimentally with present equipment, yet the object of this part of the study was to

compare the precision obtained at 1-mm. traversing interval with that yielded by the 4-mm. interval, since the former was the smallest practical interval and the latter meets the requirement of true Rosiwal analysis for this particular rock.

It was therefore decided to treat the data for the 0.9-, 1.0- and 1.1-mm. intervals as a single group, thus obtaining thirty analyses for the range 0.9-1.1, to compare with 20 at 2 and 40 at 4 millimeters. In actual practice a range as great as 0.2 mm. in the traversing interval is probably the rule rather than the exception. The procedure used here does not duplicate routine conditions precisely, however, because of the regularity of interval within each analysis; it was adopted only because there seemed no alternative. Table 3 shows the results of this recomputation, as compared to the previously given values for the 2- and 4-mm. intervals.

TABLE 3. STANDARD DEVIATIONS OF THE COMPOSITE SMALL INTERVAL GROUP AS COMPARED TO RESULTS FOR 2- AND 4-MM. INTERVALS

Traverse interval, mm.	Number of analyses	Standard deviation (per cent of whole)			
		Quartz	Feldspar	Mica	Epidote
0.9-1.1	30	1.08	1.93	0.94	0.47
2.0	20	2.63	3.56	1.78	0.65
4.0	40	4.10	4.47	2.06	0.99

Further discussion of these results is deferred until we are in a position to compare them with the total variance developed by combined analytical error and sample variance. Since the total variance was estimated from analyses made with a 1-mm. traverse interval, only the first row of Table 3 is of interest in the discussion that follows.

TOTAL VARIATION OF A GROUP OF THIN SECTIONS

Eleven thin-section samples were cut at 1-inch intervals along a 1-foot length of AX core. The original tablet from which each thin section was ground was a circle of about 1-inch diameter, but to insure that successive analyses would be made on the same area a circle $\frac{3}{4}$ inch in diameter was drawn on each finished slide, and the measurements described below were confined to the area so outlined. A linear analysis of each slide with 1-mm. traverse interval was then made on the Hurlbut and Wentworth instruments. The results of these analyses are shown in Tables 4 and 5.

TABLE 4. HURLBUT ANALYSES OF ELEVEN THIN SECTIONS, TRAVERSE INTERVAL 1 MM.

Slide No.	Quartz, per cent	Feldspar, per cent	Mica, per cent	Epidote, per cent
1	26.14	61.44	9.80	2.62
2	24.82	64.55	8.40	2.23
3	27.91	62.85	8.09	1.15
4	27.35	63.94	7.35	1.36
5	29.60	63.63	6.00	0.77
6	32.19	55.95	9.12	2.74
7	26.42	66.82	5.80	0.96
8	34.17	55.13	9.38	1.32
9	31.23	63.59	4.32	0.86
10	35.28	53.26	9.24	2.22
11	30.71	60.10	7.74	1.45

TABLE 5. WENTWORTH STAGE ANALYSES OF ELEVEN THIN SECTIONS, TRAVERSE INTERVAL 1 MM.

Slide No.	Quartz, per cent	Feldspar, per cent	Mica, per cent	Epidote, per cent
1	29.78	59.70	8.90	1.62
2	27.32	64.02	6.52	2.14
3	32.37	58.38	8.36	0.89
4	31.60	60.51	7.12	0.77
5	31.14	63.04	4.60	1.22
6	33.81	53.80	11.11	1.28
7	26.52	67.55	4.90	1.03
8	34.41	57.78	6.78	1.03
9	31.99	61.34	6.01	0.66
10	36.83	51.92	9.87	1.38
11	29.08	62.05	8.13	0.74

In Table 6 the statistics necessary for comparison of the results are shown. These include for each constituent the mean (\bar{x}), the variance or mean square of the deviations (V), the standard deviation or square root of the mean square (s) and the standard error or standard deviation of the mean ($s_{\bar{x}}$).

The differences between the quartz and feldspar means as determined on the two instruments are small in relation to the standard errors of these means, but in all the work so far done by the writer the sense of this difference is the same; the mean of a group of Hurlbut quartz values is almost invariably a little lower than that of Wentworth quartz values for the same slides; conversely, Hurlbut feldspar estimates are a little

higher. Comparison of the quartz values of Tables 4 and 5 shows that in only three instances (Nos. 1, 3 and 4) do the paired values differ by more than the standard deviation of either group considered separately (see Table 6), and in no case is the difference as great as $2s$. This difference is also not large in relation to the precision with which either machine may be operated, but the Hurlbut quartz value is smaller than the respective Wentworth value in more than 50 of a total of 60 such pairs accumu-

TABLE 6. STATISTICS COMPUTED FROM DATA OF TABLES 4 AND 5

Constituent		Hurlbut stage	Wentworth stage
Quartz	\bar{x}	29.62	31.35
	V	11.66	9.42
	s	3.42	3.08
	$s_{\bar{x}}$	1.03	0.93
Feldspar	\bar{x}	61.02	60.01
	V	19.89	20.03
	s	4.45	4.52
	$s_{\bar{x}}$	1.34	1.36
Mica	\bar{x}	7.75	7.48
	V	3.02	4.06
	s	1.74	2.02
	$s_{\bar{x}}$	0.52	0.61
Epidote	\bar{x}	1.61	1.16
	V	0.50	0.19
	s	0.71	0.44
	$s_{\bar{x}}$	0.21	0.13

lated to date. The discrepancy is apparently systematic rather than random even though its size can not be precisely determined with the methods described here.³

But this very small, non-random difference in the means for quartz and feldspar has not affected the statistics describing the variability of the sample. For the three principal constituents the differences between the Hurlbut and Wentworth estimates of V , s and $s_{\bar{x}}$ are not greater than might be expected if both runs had been made on either of the two machines, and either set of data may be used for the remaining calculations.

³ On the assumption that the differences should be evenly distributed with regard to sign, χ^2 may be computed as $2(50 - 30)^2/30 = 26.7$, whereas the 0.01 point for 1 degree of freedom is only 6.6. Cf. Snedecor, G. W., *Statistical Methods* (1940), p. 6 and table p. 163.

The question of how extensive a measurement would be required to obtain a mean of known error has been raised intermittently since Rosiwal's original publication. For the present experiment this information may be obtained from the s values of Table 6. The standard error of the mean is given by

$$s_{\bar{x}} = \frac{s}{\sqrt{n}}$$

and if it is desired only that the probability of $s_{\bar{x}}$ not exceeding some given value a be 65 per cent, the proper value of n is given by

$$n = \left(\frac{s}{a} \right)^2.$$

If one wishes a 95 per cent assurance that $s_{\bar{x}}$ will not exceed a , then

$$s_{\bar{x}} = 2s/\sqrt{n}$$

and

$$n = 4(s/a)^2.$$

In our case n is the number of thin sections of 0.44 square inch area which must be analyzed. Letting $a=1\%$ of the total, the Hurlbut s values from Table 3 yield the following results:

Constituent	Number of slides (n) required to assure $s_{\bar{x}}$ not in excess of 1% of total with	
	65% probability	95% probability
Quartz	12	47
Feldspar	20	79
Mica	3	12
Epidote	1	2

To reduce the largest error, that for feldspar, to 1 per cent with 65 per cent probability would require about 8 hours' work on the Hurlbut stage or about 24 with the Wentworth instrument. It must be remembered that the slides used in the experiment are very closely spaced, and that the means and their errors apply strictly only to the original length of core. Results for another length of core drilled from the same block are very similar (see Table 8), and it may therefore be concluded that the slides represent the cores and the cores are an adequate sample of the block. Whether the block is a good sample of the quarry is a matter concerning which sufficient evidence has not been obtained.

On the other hand, we do have evidence (see Table 8 and related text) that the variability between thin sections can be materially reduced by moderate enlargement of the area of traverse. Preliminary experiments indicate that the total variance for either quartz or feldspar can be reduced by nearly half (the standard deviations reduced by about 25 per cent) if the area traversed is increased from 0.44 to 0.78 square inch. Analyses of 42 small and rather poor thin sections spaced at 6-inch intervals along continuous EX core indicate that in this particular case such an enlargement of area would compensate the increase of variance occasioned by a five- or six-fold expansion of the distance between thin section samples. This conclusion, of course, can not be applied *a priori* to any other rock or even to any other granite, but it does suggest that a few detailed studies made with thin-section areas of a square inch or more might place the whole subject of linear analysis in a new light.

PRECISION OF A SINGLE ANALYSIS IN RELATION TO VARIATION OF THIN SECTIONS

The V values of Table 6 are expressions of the total variation introduced both by differences between thin sections and by random errors incurred in analyzing each section. These sources of variation are evidently independent of each other, and what is required now is an estimate of how much each contributes to the total variance.

The contribution of analytical or precision error to the Hurlbut total variances is given by s^2 where s is the appropriate 0.9–1.1 mm. entry of Table 3.⁴ The variance contributions made by differences between thin sections are then obtained by subtracting these s^2 values from the Hurlbut V entries of Table 6. The first and third lines of Table 7 show the variance before and after subtraction of the portion due to analytical error.

Even in a study of variance—if, for instance, the relative effects of orientation as opposed to spacing of samples were being examined—the differences between the variances of lines 1 and 3 would scarcely be critical. Here, however, the immediate interest is the expectable range of composition of thin sections, and this is best discussed in terms of standard deviation, which is a direct index of the distribution of values.

⁴ At any rate it is not larger than this. The precision test was made when the writer had had very little experience with the machine and a good deal of evidence suggests that his proficiency has increased with practice. Any one planning extensive work of this sort should test his own precision, preferably after he is thoroughly familiar with the operation of the machine; the effect of varying the speed of traverse will probably differ from operator to operator and possibly also from rock to rock. The precision indicated in Tables 2 and 3 is readily attainable.

The standard deviations before and after the extraction of analytical error are shown in lines 4 and 5 of Table 7. The largest difference is for feldspar. From the uncorrected feldspar standard deviation one would conclude that 65 percent of all similar thin sections would yield feldspar values in the range 56.6–65.5 per cent, and 95 per cent would fall between 52.1 and 69.9 per cent. Similar estimates from the corrected feldspar standard deviation would be 57.0–65.0 and 53.0–69.0 per cent, respectively. The differences between these estimates are negligible in the present case, and it may be concluded therefore that, *if a 1-mm. traverse*

TABLE 7. EXTRACTION OF ANALYTICAL ERROR FROM TOTAL VARIANCE

	Quartz	Feldspar	Mica	Epidote
Total variance, Hurlbut	11.66	19.89	3.02	0.50
Variance due to precision error	1.17	3.72	0.88	0.22
Sample variance	10.49	16.17	2.14	0.28
Total standard deviation	3.42	4.45	1.74	0.71
Standard deviation after extraction of precision error	3.25	4.03	1.47	0.53

interval is used, the error incurred in analyzing a single slide is so much smaller than the variation between thin sections that no special account of it need be taken.

Table 6 indicates that this conclusion, which is based entirely on experiments with the Hurlbut stage, may be quite safely extended to the Wentworth instrument, for it will be remembered that the same sample was used in both runs. The contribution of the sample to the total variance is therefore the same, and since the total variances are very similar for the three major constituents it follows that the precision with which the Wentworth machine may be operated does not differ significantly from that which may be attained with the Hurlbut instrument.⁵

PRECISION IN RELATION TO TRAVERSE INTERVAL AND GRAIN SIZE

With the conclusion that in this case the analytical or precision error of a 1-mm. interval analysis is small enough to be neglected, the main outlines of the argument are complete. But considerable more generally applicable information may be drawn from Tables 1, 2 and 3.

⁵ There is reason to suspect that the Wentworth stage is preferable for analyses involving very small grains of minor constituents, and the epidote figures in Table 6 are in this respect typical of results obtained in a good many shorter, less carefully controlled experiments. The only point of consequence here is that the precision error of the Wentworth stage, is not larger than that of the Hurlbut stage, for it has already been shown that the precision error of the latter may be safely neglected for present purposes.

On the thin section used for the precision test, no grain was measured more than once with a 4-mm. traverse interval, while with all smaller intervals duplicate or multiple measurements were unavoidable, and, of course, their frequency increased as the interval was reduced. With the 1-mm. interval nearly all quartz and feldspar and a great many mica grains were measured at least twice. Yet it is clear from Table 1 that the mean values are not significantly affected by variation of traverse interval. As long as the traverses are evenly spaced no systematic error is introduced by duplicate or multiple measurements of the same grains.

Tables 2 and 3, on the other hand, clearly indicate that the precision of a single analysis is greater the smaller the traverse interval with which it is made. Where the composition of individual thin sections is desired, the smallest practical traverse interval will give the most precise result. Using the quartz figures of Table 3 as an example, a single 1-mm. analysis will fall, with 2/1 probability, within 1.1 per cent of the true⁶ composition of the slide, and the chances are 19/1 that it will not be in error by more than 2.2 per cent, while for a single 4-mm. analysis the equivalent ranges are 4.1 and 8.2 per cent.

It may be noted in passing that this direct variation of precision error and traverse interval seems independent of grain size. In the thin section used for the precision test, epidote grains were no more than a few tenths of a millimeter in maximum diameter, mica grains were on the order of 1 mm., and quartz and feldspar grain diameters were nearly all between 2 and 4 mm., with the latter mostly more and the former mostly less than 3 mm. Yet the sense of the variation of precision error with traverse interval is the same throughout; it would require a much more extensive measurement to determine whether its rate is affected by grain size, though this seems quite probable.

These conclusions deal only with the problem of determining the composition of a single thin section, and they are compatible with what might have been predicted from a consideration of the "trapezoid rule" commonly used in determining the areas of irregular figures.⁷ But the

⁶ "True" in the sense that it will be the mean of a very large number of analyses of the same area made at any traverse interval.

⁷ $A = w(\frac{1}{2}y_0 + y_1 + y_2 + \dots + y_{n-1} + \frac{1}{2}y_n)$, cf., for instance, Marks, L., *Mechanical Engineers Handbook*, 4th Ed., McGraw Hill Co., p. 2029 (1941). The accuracy of the result varies directly with n and inversely with w . In our case w is the traverse interval, y is the traverse length within a single grain (or in all grains of a single mineral), and n is the number of traverses in a grain (or in all grains of a single mineral). In linear analysis one determines only the ratios of areas to each other, thus:

$$\frac{A_1}{A_2} = \frac{w_a(\frac{1}{2}y_{a_0} + y_{a_1} + y_{a_2} + \dots + y_{a_{n-1}} + \frac{1}{2}y_{a_n})}{w_b(\frac{1}{2}y_{b_0} + y_{b_1} + y_{b_2} + \dots + y_{b_{n-1}} + \frac{1}{2}y_{b_n})}$$

object of linear analysis is nearly always the determination of the composition of some large and usually unknown volume of rock, and it is in this connection that both Rosiwal and Lincoln and Reitz specifically require that no grain be measured more than once. In Table 8 are shown results for the analysis on the Hurlbut stage of a second suite of 11 sections, prepared from the same block and in the same fashion previously described. In these analyses the entire area of the slide (approximately 1 square inch) was traversed for each analysis, and the error of the mean for each constituent is smaller than for the analyses shown in Tables 4, 5 and 6.

TABLE 8. COMPOSITION OF SECOND SUITE OF ELEVEN THIN SECTIONS

	Quartz	Feldspar	Mica	Epidote
Mean of 1-mm. traverse-interval analyses	29.4	62.0	7.2	1.4
Standard error of mean	0.8	1.0	0.5	0.1
Mean of 4-mm. traverse-interval analyses	29.8	61.1	7.8	1.3
Standard error of mean	1.7	1.7	1.1	0.2
4-mm. analyses summed as a single Rosiwal analysis	29.8	61.2	7.7	1.3

From comparison of Tables 6 and 8 it is evident that the conclusions drawn from the single-slide precision test may be safely applied in combining the results for many thin sections providing the orientation and areas of the thin sections are uniform. The error of the mean is much less for the 1- than for the 4-mm. values, while for the Rosiwal summation it is unknown.

SUMMARY

Where the composition differences between thin sections are of the order of a few per cent and the constituents being measured are present in excess of five per cent, the estimate of thin-section variability is not significantly affected by the random errors incurred in analysis of the thin sections, providing the traversing interval is 1 mm. or less.

To obtain mean values for the Woodstock granite whose standard errors would in each case be less than 1 per cent of the total with 2/1 probability would require 1-mm. traverse-interval analysis of 20 thin

If the traverse interval is held constant, as in the Wentworth procedure, $w_a = w_b$, and the areas will be related to each other as the ratio of the total traverse distances. From this all the conclusions so far stated in this section may be seen to follow.

sections of 0.44 in.² area for feldspar, 12 for quartz, 3 for mica, and 1 for epidote. If thin-section areas are as much as 0.77 in.² similar precision would be obtained with only 11 slides for feldspar and fewer for other constituents.

The precision error of a single analysis varies directly with the traverse interval, and its variation is independent of grain size as long as magnification is sufficient to permit ready identification of all grains. The precision of the Wentworth machine is essentially the same as that of the Hurlbut stage, except that in the writer's case the former gives somewhat better results for minor constituents present in small grains.

The mean of a group of 1-mm. linear analyses does not differ significantly from a true Rosiwal analysis of the same group of slides, or from the average of linear analyses of these slides made with a traverse interval large enough to eliminate duplicate measurements. But the precision of the 1-mm. mean is superior to that of the mean based on larger traverse interval. For the analyses reported in Table 8, for instance, the number of slides required to achieve a mean of some known precision with traverse interval of 4 mm. is between three and five times as great as would be required if a 1-mm. traverse interval were used.

The procedure suggested by Wentworth, in which traverses are regularly spaced regardless of grain size, is thus superior to the regular Rosiwal procedure, in which the maximum grain diameter sets an arbitrary lower limit to the spacing of traverses. In fact, precision readily obtained with the Wentworth procedure is of such an order as to suggest that valuable results might accrue from carefully planned variance studies of any rock suitable for linear analysis, even if no close correlation with volume, specific gravity or chemical composition were attempted.

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felder; all other analytical work is by the author, who is of course solely responsible for the views expressed.

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OLIVINE FROM NORTHERN CALIFORNIA SHOWING PERFECT CLEAVAGE*

H. E. HAWKES, JR.

ABSTRACT

Olivine showing perfect cleavages on the (010) and (100) crystal planes is described from a dunite near Dunsmuir, Siskiyou County, California. Because of its striking resemblance to pyroxene both in hand specimen and thin section, previous workers have misidentified the mineral as pyroxene, and the rock which contains it as pyroxenite or peridotite.

INTRODUCTION

Unusual olivine showing perfect cleavages parallel to the (010) and (100) crystal planes was identified in dunite from the vicinity of the Little Castle Creek chromite mine, known also as the Castle Crags or Brown mine, in the Siskiyou Mountains of northern California. Specimens for detailed study were collected on the south side of Little Castle Creek canyon about two miles southwest of Dunsmuir, near the boundary of Shasta and Siskiyou Counties, during the winter of 1940-41. The work on the olivine grew out of a geological investigation of the chromite deposits of the Little Castle Creek area by the Federal Geological Survey. A summary of the results of this investigation, with maps of the surface and underground geology, was released to the public in 1943.¹

PREVIOUS WORK

The cleavages of the olivine have confused previous workers in the area, who identified the mineral as pyroxene and the rock in which it occurs as pyroxenite or peridotite. Diller² states, "The country rock of the chromite ore body (Little Castle Creek mine) is in part peridotite but chiefly pyroxenite, which exhibits large cleavage surfaces often several feet in extent." J. E. Allen³ also mentions the presence of peridotite and pyroxenite from the vicinity of the Little Castle Creek mine. No pyroxene has been identified by the author in a suite of more than 50 thin sections prepared from the ultramafic rocks of this area, so that it may be presumed that Diller and Allen were referring to rocks containing cleavable olivine. On basal sections the extinction of olivine will be parallel to the

* Published by permission of the Director of the Geological Survey, U. S. Department of the Interior.

¹ Hawkes, H. E., Chromite deposits of Little Castle Creek area, Shasta and Siskiyou Counties, Calif.: *U. S. Geological Survey*, Strategic Mineral Investigations, Preliminary maps, Press Notice released August 6, 1943.

² Diller, J. S., Chromite: *U. S. Geol. Survey, Min. Res.* (1916), pt. 1, 29.

³ Allen, J. E., Geological investigation of the chromite deposits of California: *Calif. Jour. Mines and Geol.*, **37**, 129-132 (1941).

cleavages (010) and (100), whereas in pyroxene it will be symmetrical with respect to the cleavage (110). This simple method of distinguishing the two minerals has apparently been overlooked by the workers who misidentified the mineral.

The literature contains many references to the chromite deposits of the area.⁴ The only report touching on the general geology is by C. V. Averill,⁵ who includes a map showing the areal geology of the part of the Shasta quadrangle within which the area in question lies.

Olivine showing well-developed cleavages has been described in dunite from Buck Creek, North Carolina, by Pratt and Lewis.⁶ They say, "The olivine is colorless in thin section and never shows crystal boundaries. It is generally cracked irregularly, particularly in the beginning of the change to serpentine. It also frequently exhibits well-developed parallel cracks representing the brachypinacoidal cleavage, and sometimes distinct basal cleavage, as well. In a basal section, cleavage parallel to the macropinacoid can often be seen also. The grains usually average from 0.5 mm. to 1 mm. in diameter, though isolated individuals of 5 mm. to 6 mm. are sometimes seen."

GEOLOGY AND PETROGRAPHY OF THE DUNITE

The dunite at Little Castle Creek is part of a larger mass which extends over a considerable area south and southwest of Dunsuir, as shown on the geologic map of the Shasta quadrangle by Averill.⁷ The regional structure is complicated by intrusions of granodiorite and gabbro which are believed to be later than the dunite.

Although part of the dunite of the Little Castle Creek area is composed of olivine that shows very conspicuous cleavage, a large part is also made up of normal olivine. Time did not permit a study of the regional distribution of these two types of olivine, although such an investigation would be highly desirable. Olivine showing similar perfect cleavages was

⁴ Diller, J. S., Chromite: *U. S. Geol. Survey, Mineral Res.* (1916), Pt. 1, 28-30.

Diller, J. S., Chromite in the Klamath Mountains, California and Oregon: *U. S. Geol. Survey, Bull.* **725**, 20-22 (1921).

Johnston, W. D., Nodular, orbicular, and banded chromite in northern California: *Econ. Geol.*, **31**, 417-427 (1936).

Bradley, W. W., et al., Manganese and chromium in California: *Cal. State. Min. Bur., Bull.* **76**, 183-188; 191-193 (1918).

Allen, J. E., *op. cit.*

⁵ Averill, C. V., Preliminary report on the economic geology of the Shasta quadrangle: Mining in California; *California, Dept. Nat. Res., Div. Mines*, **27**, 17-24; 27 (1931).

⁶ Pratt, J. H., and Lewis, J. V., Corundum and the peridotites of North Carolina: *North Carolina Geol. Surv.*, **1**, 73 (1905).

⁷ Averill, C. V., *op. cit.*

noted at the Lucky Strike chromite prospect, about four miles west-southwest of the Little Castle Creek area; it is possible, therefore, that cleavable olivine is widely distributed in the dunite.

MEGASCOPIC APPEARANCE

On hand-specimen or outcrop surfaces the olivine cleavage, where well developed, gives the rock a very conspicuous sparkling appearance, similar to that of pyroxenite, anorthosite, or coarse-grained marble. Typical hand specimens of the rock were, in fact, frequently called anorthosite by experienced petrographers. With a hand-lens, cleavage in two directions at right angles to one another can be distinguished in many crystals. Weathered surfaces commonly are smooth and show the characteristic buff or buckskin color of dunites, which is the result of the oxidation of the iron contained in the olivine. On fresh, unweathered surfaces the rock is generally a deep green to medium gray.

Texture

In thin section, the Little Castle Creek dunite is seen to be made up of aggregates of olivine grains in subparallel orientation. The aggregates commonly range in size from 10 mm. to 40 mm., and the individual grains within the aggregates from 0.05 mm. to 4 mm. In a hand specimen the aggregates are easily mistaken for homogenous crystals. Diller was probably referring to these large aggregates when he spoke of "large cleavage surfaces often several feet in extent." The texture is allotriomorphic, and the individual olivines commonly show polygonal outlines.

The aggregate texture is tentatively believed to be the result of crushing of original large olivine crystals, accompanied by slight rotation of the fragments.

Fabric

In hand specimens of the dunite, the olivine cleavages appear as brilliantly reflecting surfaces, and hence can be used as a qualitative guide to the rock fabric. In certain localities the crystal aggregates appear to be statistically oriented, as seen by the subparallel arrangement of the major cleavage surfaces. This orientation gives the rock a planar structure and in places even a moderately well-defined cleavage or fissility. This is apparently identical to structures described by Turner.⁸ Ross

⁸ Turner, F. J., Preferred orientation of olivine crystals in peridotites: *Trans. Royal Soc., New Zealand*, **72**, 288-290 (1942).

and Thayer have also found a similar structure in very coarse-grained dunite southwest of the Woods mine in Lancaster County, Pennsylvania.⁹ It is believed that systematic regional mapping of this foliation in the Little Castle Creek area is desirable, as it would be necessary for a complete picture of the structural petrology of the dunite mass. A regional fabric analysis of an area of equal extent in the average, non-fissile ultramafic mass would require the preparation of a prohibitive number of orientation diagrams.

Accessory Minerals

Accessory chromite in rounded grains up to 1 mm. occurs throughout the dunite, but rarely makes up more than one per cent of the rock. No pyroxenes were found in the dunite.

Secondary Minerals

Serpentine is present in a few of the thin sections examined and rarely makes up as much as 50 per cent of the total volume of the rock. Bladed chlorite is developed along crystallographic directions of many olivines, and magnetite, talc, carbonates, and fine stringers of chrysotile are locally present. In the zone of weathering, red iron oxides have been produced by breakdown of the olivine.

MINERALOGY OF THE OLIVINE

Twinning and Undulatory Extinction

Twinning on the (100) composition plane is common in the dunite which carries cleavable olivine. This is identical in appearance to that figured by Rogers and Kerr.¹⁰

Undulatory extinction of olivine, resembling that in the quartz of strained quartzites, was observed in some of the specimens studied. In the Little Castle Creek mass it appears to be confined to dunite containing cleavable olivine, but it is not everywhere present. No correlation could be made between the prevalence of twinning and the degree to which undulatory extinction had been developed.

Cleavages

The best cleavage is normal to X, or parallel to (010); the other principal cleavage is normal to Z, parallel to (100). Cleavages parallel to (001)

⁹ Ross, C. S., and Thayer, T. P., personal communications.

¹⁰ Rogers and Kerr, *Thin-section Mineralogy*, McGraw-Hill Book Co., p. 294 (1942).

and (110) were observed in a very few grains. Several other apparent cleavages opened up during the grinding of the slides but could not be definitely correlated with simple crystal planes.

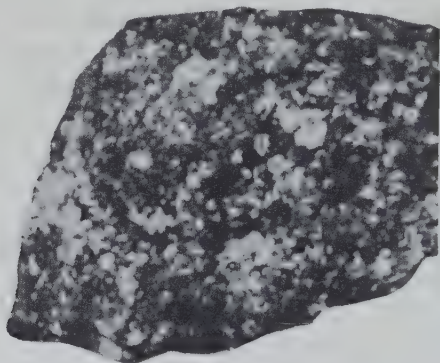


FIG. 1. Photograph of hand specimen of dunite from Little Castle Creek. White areas are caused by reflection of light from olivine cleavage surfaces. Natural size.

Optical Properties

As far as could be determined, the optical properties of cleavable olivine are identical with those of normal olivine collected from the same general area. Miss J. J. Glass determined the optical properties of one specimen of cleavable olivine with these results:

$$\begin{array}{lll}\alpha=1.649 & \beta=1.666 & \gamma=1.684 \\ 2V \text{ close to } 90^\circ, \text{ dispersion noticeable.}\end{array}$$

Clarence S. Ross found the optical properties of a specimen to be as follows:

$$\begin{array}{ll}\alpha=1.650 & \gamma=1.683 \\ \text{Axial angle not measured, but is near } 80^\circ.\end{array}$$

Chemical Composition

A sample taken from the specimen by Miss Glass and analyzed in the Geological Survey laboratories was described by Michael Fleischer as follows:

"The thin section examined showed that the sample contained chlorite, introduced along crystallographic directions of the olivine, and also a little magnetite. The chlorite was removed by repeated treatments with methylene iodide, after which the magnetite was removed with the electromagnet."

		Molecular Ratio	
SiO ₂	40.84	.680	or 1.00
MgO	50.27	1.247	
FeO	8.18	0.114	1.366 or 2.01
NiO	0.19	0.003	
MnO	0.17	0.002	
Fe ₂ O ₃	0.13		
Al ₂ O ₃	0.19		91.3 mol. % Mg ₂ SiO ₄
TiO ₂	0.04		8.7 mol. % Fe ₂ SiO ₄
H ₂ O	0.37*		
<hr/>			
100.38			

* Includes a little methylene iodide.

$$D_4^{25} = 3.30$$

X-ray Pattern

X-ray diffraction patterns of cleavable olivine prepared by W. E. Richmond of the Survey are identical with similarly prepared photographs of ordinary olivine, and show no similarity to photos of standard ortho- and clino-pyroxene.

SIGNIFICANCE OF THE CLEAVAGE

The cleavages are believed to have been developed early in the metamorphic history of the rocks, or possibly during the crystallization of the olivine. The deformed cleavages shown in Fig. 2c indicate deformation of the olivine after the cleavage was developed. The bladed chlorite which replaces the olivine along cleavages and other crystallographic directions seems to be mainly associated with, but not restricted to dunite containing the highly cleaved olivine. The prevalence of chlorite along rectilinear lines might be attributed entirely to emplacement controlled by crystal structure, but the number of cleavages free of chlorite suggests that they developed before the chlorite came in.

No satisfactory evidence bearing on the origin of the cleavage was discovered. The development of cleavage may be related in some way to the absence of serpentine in the Little Castle Creek dunite. Serpentine-free dunite may yield to stress by an accentuation of olivine cleavages in contrast to ordinary serpentine-bearing ultramafic rocks which fail by micro-shearing of serpentine zones. Simple cataclastic or protoclastic crushing however, can not invariably produce cleavage in olivine, as intensely crushed olivine in fresh dunite from the Twin Sisters Mountains in Washington has no better cleavage than ordinary olivine.¹¹

¹¹ Thayer, T. P., Personal communication.



FIG. 2

A. Photomicrograph showing rectangular cleavage pattern, with chlorite (arrows) along some cleavages, Little Castle Creek area. Plain light, $\times 28$.

B. Photomicrograph showing rectangular cleavage pattern in another grain of same slide, and greater development of chlorite (arrows) in zone along one side. Note that although chlorite occurs in all of major cleavage cracks, it does not appear to be present in finer cracks. Plain light, $\times 28$.

C. Photomicrograph showing chlorite along bent cleavages in olivine in partly altered dunite, Little Castle Creek area. All of olivine in field is part of a single grain. Plain light, $\times 28$.

D. Photomicrograph showing cleavage in olivine from dunite mass on Buck Creek, N. C. Note development of chlorite along wider cracks. Opaque mineral is secondary magnetite. Collected by C. S. Ross. Plain light, $\times 28$.

ACKNOWLEDGMENTS

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NEPHELINE SYENITE FROM BEEMERVILLE, SUSSEX COUNTY, NEW JERSEY

A. S. WILKERSON,

Rutgers University, New Brunswick, New Jersey*

ABSTRACT

A petrographical study of an intrusion of nepheline syenite in northwestern New Jersey reveals the presence of fluorescent hackmanite. Ten new mineral analyses of the syenite are presented.

INTRODUCTION

During July, 1945, A. K. Snelgrove, Director of Rutgers University Bureau of Mineral Research, M. E. Johnson, New Jersey State Geologist, and the writer visited the nepheline syenite area near Beemerville, Sussex County, New Jersey. A study of the syenite was undertaken to determine the commercial possibilities of the rock for the ceramic industries, especially for glass manufacture. Results obtained from this study will be published by the writer and J. E. Comeforo† as a bulletin of the Bureau.

GEOLOGY OF AREA

The southernmost end of the intrusion of nepheline syenite is slightly more than one mile northwest of Beemerville or about 10 miles northwest of Franklin, in the northwestern part of the State. The intrusion forms a terrace on the lower part of the eastern slope of Kittatinny Mountain. The intrusion, probably a lenticular sill but possibly a dike, is roughly elliptical in plan, is about 2 miles long, and not more than 800 or possibly 900 feet wide at its broadest part. Its northeastward trend is parallel to the strike of the associated bedded rocks—the Shawangunk conglomerate of Silurian age to the west and possibly lying on the syenite, and the Ordovician Martinsburg shale to the east and possibly beneath the syenite.

The area is wooded, outcrops are few and poor, and contacts are obscured. The relief of the area is low but the topography is rough due to numerous mounds which are separated by depressions.

Although the bulk of the intrusion is nepheline syenite, it varies considerably both in texture and mineral composition along its strike, and grades into other phases locally. It is cut by narrow dikes of leucite-

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† Research Associate, Bureau of Mineral Research.

tinguaite.¹ Porphyritic facies likewise occur. These are not exposed in a manner which permits their relationship to the syenite proper to be discerned. The porphyry areas are small.

Kemp² places the age of the intrusion as post-Silurian and pre-Triassic.

PETROGRAPHY

The nepheline syenite is medium to dark gray in color. It has almost invariably a granular texture, but locally it is trachytoidal. Many samples are of medium-size grain, but others are coarse grained. A megascopic examination reveals nepheline, feldspar, biotite, pyroxene, and magnetite. Normally the nepheline possesses a greasy luster and is dark in color due to inclusions. Some specimens contain a quantity of magnetite sufficient to appreciably affect the needle of a Brunton compass when brought close to the compass.

Under a mercury-vapor light many samples fluoresce, sometimes as high as fifty per cent of the surface fluorescing in an orange color. A study of colorless, isotropic, fluorescent fragments in immersion liquids shows the material to have an index of refraction of 1.487, that of hackmanite. Hackmanite (variety of sodalite) has not previously been reported from this area.

Under the microscope most specimens are hypautomorphic-equigranular. Cataclastic texture is local. Some orthoclase and nepheline show fractures extending through adjacent minerals. Also peripheral crushing of grains was noted and in some instances almost complete crushing of some of the crystals into smaller grains. The syenite is composed of orthoclase feldspar, nepheline with or without accompanying sodalite (variety hackmanite), either aegirine or aegirine-augite, biotite rich in iron, and a small quantity of melanite garnet unevenly distributed throughout the rock. Plagioclase feldspar occurs only in minute amounts in some specimens and is absent from others. Magnetite, apatite, sphene, and small amounts of fluorite, zircon, and pyrite occur as accessories.

The outline of orthoclase crystals is generally allotriomorphic. Some are twinned according to the Carlsbad law. The size seldom exceeds 17 mm. \times 6 mm., but locally may be about 2 inches long. Crystals of feldspar contain much nepheline poikilitically included, and also contain inclusions of all other primary minerals. Portions of crystals are altered to a clay-like material and to cancrinite.

Nepheline is euhedral to subhedral and seldom exceeds 10 mm. \times 7 mm.

¹ Wolff, J. E., Leucite tinguaite from Beemerville, N. J., Harvard Coll. Mus. C. Z. Bull. 38 (Geol. Ser. 5), 273-277 (1902).

² Kemp, J. F., The elaeolite syenite near Beemerville, Sussex County, New Jersey: *N. Y. Ac. Sci., Tr.* 11, 71 (1892).

in size. Its index of refraction being greater than orthoclase, nepheline stands out in relief when enclosed in the feldspar. Inclusions are magnetite, apatite, sphene, biotite, pyroxene, and infrequently some orthoclase. The usual decomposition product is cancrinite, but some colorless mica is present as well as a colorless, birefringent, radiating zeolite (?).

Some sodalite, variety hackmanite, is found in practically all specimens. Some specimens have the sodalite concentrated in planes, and it is these specimens which are beautifully fluorescent. Sodalite normally is anhedral to subhedral, but where euhedral dodecahedral outlines are observed. It frequently fills veinlets in fractured nepheline and orthoclase. Crystals seldom measure more than 2.50 mm. \times 1.50 mm.

The most common ferromagnesian minerals are aegirine-augite and aegirine. These soda-bearing monoclinic pyroxenes are not found together in the same specimen, however. Aegirine-augite is about twice as abundant as aegirine. These pyroxenes occur in crystals with irregular outline, sometimes better defined in the prismatic zone, less often well-defined on the basal pinacoid. Crystals are never terminated. Aegirine-augite has marked pleochroism with X=olive green, Y=olivine green and Z=yellowish green; aegirine has strong pleochroism with X=clear green, Y=yellowish green, and Z=yellowish brown. The maximum size of crystals is 3.50 mm. \times 1.25 mm.

Characteristic of the syenite is a golden-brown to dark reddish-brown biotite with strong absorption. The mica occurs as subhedral and anhedral crystals as well as in shreds. Crushed fragments of the rock under a binocular, however, reveal well-formed pseudo-hexagonal "books." The mica is closely associated with the pyroxenes, magnetite, and sphene. The maximum size of crystals is 3.25 mm. \times 1.00 mm.

Garnet, variety melanite, is not uniformly distributed throughout the intrusion, but at a few localities it comprises almost 4 per cent of the mineral assemblage. It attains a maximum size of 2 mm. in diameter. Some melanite contains inclusions of magnetite, pyroxenes, biotite, and a small amount of nepheline.

Colorless apatite, usually as stout prisms or rounded basal sections, attains a maximum size of about 0.7 mm. \times 0.1 mm. It is included in all the primary minerals.

Magnetite is found in well-developed crystals, subhedral crystals, and as anhedral. The maximum size is 1.50 mm. in diameter. It is usually unaltered, but a small amount has changed to hematite. It is intimately associated with biotite, pyroxenes, and sphene and is also included in these minerals as well as in the feldspar and feldspatoids.

Well-formed wedges with rhombic sections, and subhedral and anhedral crystals of sphene are numerous. Some of the crystals are twinned.

Seldom do the crystals exceed 2.25 mm. in length by 2 mm. in width. Sphene appears in two generations, one very early and the other late in the sequence of crystallization.

Zircon is present in a few very minute crystals. Purple fluorite, soda-rich plagioclase, and pyrite occur in traces in some specimens. Eudialyte, eucolite, or other similar minerals were not recognized as being present in the specimens examined.

Although Emerson,³ Kemp,⁴ Iddings,⁵ Wolff,⁶ and Auroousseau and Washington⁷ have studied the Beemerville syenite only two mineral analyses are given in terms of percentage mineral composition.⁸ Ten other mineral analyses are here presented. The first three are from the southern third of the intrusion, numbers 4 through 7 from the middle third, while 8 through 10 are from the northern third. Analyses 11 and 12 are those presented by Wolff. Number 13 is the average.

	1	2	3	4	5	6	7	8	9	10	11	12	13
nepheline	73.0	41.5	45.8	52.6	43.5	37.3	50.1	47.3	25.8	31.4	74.2	9.8	44.4
orthoclase	6.0	37.5	39.4	34.6	20.0	40.4	22.4	39.4	62.6	47.7	9.5	72.3	36.0
sodalite	tr	—	tr	2.8	0.8	tr	1.5	1.0	0.3	5.0	—	—	0.9
aegirine	—	—	—	—	—	0.5	—	9.1	8.8	13.3	—	—	8.8
aegirine-augite	11.9	5.0	7.0	1.7	16.9	—	7.6	—	—	—	8.7	15.4	
biotite	3.2	6.9	1.6	4.0	5.7	12.8	11.2	0.2	0.6	tr	1.8	0.2	4.0
sphene	4.2	5.6	3.3	0.8	6.8	4.8	5.4	2.4	1.4	2.5	5.3	2.0	3.7
magnetite	1.0	3.2	2.7	2.2	2.6	3.7	1.6	0.6	0.3	tr	—	—	1.6
apatite	0.7	0.3	0.2	tr	0.1	0.5	0.2	tr	tr	—	0.5	0.2	0.2
melanite	—	—	—	1.0	3.6	—	—	—	—	—	—	—	0.4
acid plagioclase	—	—	—	tr	—	—	—	tr	—	—	—	—	tr
fluorite	—	—	—	—	—	—	—	—	tr	tr	—	—	tr
pyrite	—	—	—	tr	—	—	—	—	tr	—	—	—	tr

³ Emerson, B. K., On a great dyke of foyaite or elaeolite syenite, cutting the Hudson River shales in n.w. New Jersey: *Am. Jour. Sci.* (3) **23**, 302-8 (1882).

⁴ Kemp, J. F., *op. cit.*, pp. 60-71.

⁵ Iddings, J. P., Nepheline-syenite from Beemerville, Sussex Co., N. J.: *U. S. Geol. Survey, Bull.* **150**, 209-211 (1898).

⁶ Wolff, J. E., Post-Ordovician igneous rocks: *U. S. Geol. Survey, Folio* **161**, 12-13 (1908).

⁷ Auroousseau, M., and Washington, H. S., The nepheline syenite and nepheline pyrophyry of Beemerville, N. J.: *Jour. Geol.*, **30**, no. 7, 571-586 (1922).

⁸ Wolff, J. E., *op. cit.*, p. 12.

MINERAL OXIDATION

A. N. WINCHELL,

*Stamford Research Laboratories, American Cyanamid Company,
Stamford, Connecticut.*

ABSTRACT

Mineral oxidation is of two radically different kinds; one is the well known oxidation during weathering which involves addition of oxygen and the other is the little known oxidation during anamorphism which involves elimination of hydrogen (but no addition of oxygen). The first destroys the primary mineral and forms new ones; the second merely modifies the primary mineral but does not destroy it. Examples of the second process are described and illustrated by diagrams.

It is very well known that oxidation is one of the important chemical processes of katamorphism, especially of weathering, but it is not as well known that the same chemical process may result from anamorphism, if conditions are favorable. However, oxidation during weathering destroys the old compounds and produces new ones, while oxidation during anamorphism may leave the old compounds intact with their characteristic crystal structures (almost) unmodified and their properties modified in no very radical way. It is possible to distinguish between these two cases by noting that oxidation during weathering is an oxidation *of* (one or more) minerals, while oxidation during anamorphism is an oxidation *in* (one or more) minerals. This difference will be more easily understood by describing a few illustrations.

OXIDATION DURING WEATHERING

Weathering destroys siderite (FeCO_3) producing CO_2 and hematite (Fe_2O_3) or limonite ($2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}?$) by oxidation (and hydration) of the iron. In a similar way it destroys pyrite, or marcasite (FeS_2), producing sulfuric acid and hematite or limonite by oxidation (and hydration). Or, again, it destroys olivine, producing serpentine and limonite by oxidation (and hydration).

Mason¹ has shown that minerals containing both iron and manganese are oxidized in two stages, all the iron being oxidized before oxidation of the manganese begins.

In all of these cases (and many more) the original mineral is destroyed and one or more new minerals are formed by oxidation, and in all these

¹ Mason, F., *Geol. För. Förh. Stockholm*, **63**, 117 (1941).

cases oxygen is added to the original mineral. The processes are so well known that further description is needless.

OXIDATION DURING ANAMORPHISM

When a mineral which contains ferrous iron and also hydroxyl (or, perhaps, in some cases, H_2O) is heated artificially or in nature under conditions which permit hydrogen to escape, the hydroxyl radical may lose hydrogen and become an atom (or ion) of oxygen, the valence bond previously satisfied by hydrogen now serving to convert an adjoining atom (or ion) of iron from the ferrous to the ferric state. The change from the hydroxyl radical to the oxygen atom is accomplished with only a little change of size and little, if any, change of shape, or position, in the crystal lattice; likewise, the change from a ferrous to a ferric atom is accomplished with only a little change of size and little, if any, change of shape or position of the iron atom in the crystal lattice. Accordingly, the oxidation of the iron occurs *inside* the mineral, with little, if any, change in its crystal structure—that is, the mineral is not destroyed, nor even changed, in any fundamental sense. Moreover, the oxidation of the iron can take place to any extent, from none at all to a hundred per cent. That is, there is a complete series from the wholly ferrous condition to the wholly ferric condition (if there is enough hydroxyl in the original mineral). It is of course possible to divide such a series into two or more parts and call each part a mineral, but such divisions have no natural basis—they are purely arbitrary and artificial—and it seems much better to consider such a series as merely different conditions of one mineral.

Certain concrete cases may serve to illustrate these general principles.

Some phosphates contain hydroxyl and ferrous iron, but they are not well known and therefore little is known regarding oxidation in them. However, ludlamite, alluaudite, and triploidite illustrate the condition. Certain hydrous phosphates contain iron which is oxidized very easily, but it is not clear whether this is accomplished in the mineral or with destruction of the mineral. Such a condition is illustrated by vivianite and sympleksite.

Biotite commonly contains both hydroxyl and ferrous iron, but it also contains so many other variables that the effects of oxidizing the iron are not yet well known. This is doubtless due in part to the presence in many biotite samples of ferric iron not derived from oxidation of ferrous iron, but a primary constituent which proxies for some aluminum.

In 1930 Barnes² proved that when common hornblende is changed to "basaltic hornblende" by heating, the change is due to loss of hydrogen

² Barnes, V. E., *Am. Mineral.*, **15**, 393 (1930).

with accompanying oxidation of ferrous iron; that is, a hornblende originally having, for example, the formula $\text{Ca}_2\text{Mg}_2\text{Fe}_2''\text{AlSi}_7\text{AlO}_{22}(\text{OH})_2$ becomes $\text{Ca}_2\text{Mg}_2\text{Fe}_2'''\text{AlSi}_7\text{AlO}_{24}$. Such a change occurs gradually and is accompanied by a gradual decrease of the extinction angle to 0° , a gradual increase of refringence and birefringence, and also in dispersion and in density, while the optic angle becomes about 60° and the color changes from green to brown. All these changes can be reversed, and the original

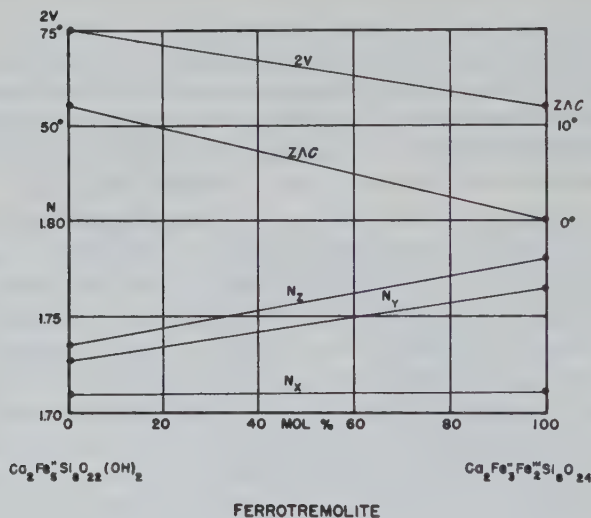


FIG. 1

condition obtained again, by reheating the mineral in hydrogen, which introduces the hydrogen once again and changes the iron from ferric to ferrous. The changes in optic properties caused by such oxidation of two atoms of ferrous iron in two end-members of the hornblende system are shown as obtained approximately by the author's recent study of calciferous amphiboles³ in Figs. 1 and 2. The first figure shows the results of oxidation of iron in ferrotremolite $\{\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2\}$ and the second figure shows the same results for $\text{NaCa}_2\text{Fe}_5''\text{Si}_7\text{AlO}_{22}(\text{OH})_2$ changing gradually to $\text{NaCa}_2\text{Fe}_3'''\text{Fe}_2'''\text{Si}_7\text{AlO}_{24}$. Other end-members of hornblende may contain some Fe''' (proxying for Al) before any oxidation of ferrous iron occurs; in spite of this complication it is clear that oxidation produces very similar results in them.

³ Winchell, A. N., *Am. Mineral.*, **30**, 27 (1945).

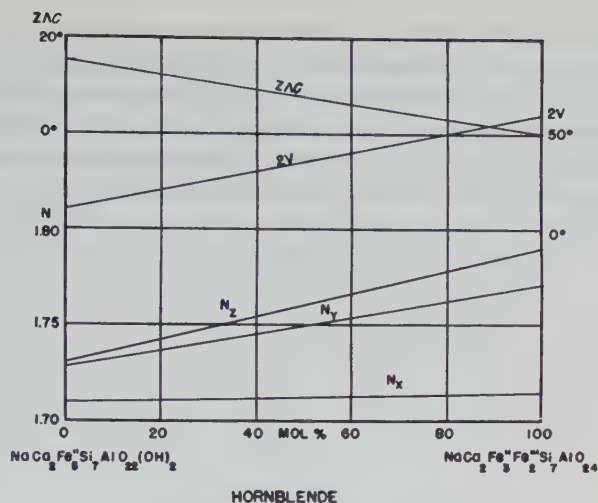


FIG. 2

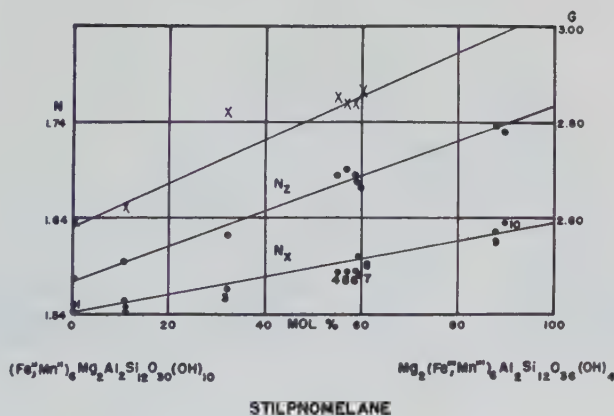


FIG. 3

Stilpnomelane is a rather rare "brittle mica" which varies in composition in many ways, but the greatest and most important variation is in the oxidation of the iron (and manganese). Disregarding other variations (since they are clearly minor in amount and in importance) the mineral varies from⁴ about $(\text{Fe}^{II}, \text{Mn}^{II})_6\text{Mg}_2\text{Al}_2\text{Si}_{12}\text{O}_{30}(\text{OH})_{10}$ to about $\text{Mg}_2(\text{Fe}^{III})_6$,

⁴ Analyses show about as much H₂O in Fe^{III}-rich stilpnomelane as in the Fe^{II}-rich type, but Hutton (*Mineral. Mag.*, 25, 172, 1938) found evidence that Fe^{III}-rich types contain less hydroxyl.

Mn''') $_6\text{Al}_2\text{Si}_{12}\text{O}_{36}(\text{OH})_4$. The very considerable variations in optic properties corresponding with this variation in composition are shown⁵ in Fig. 3.

Chlorite is a mineral which contains hydroxyl and may contain ferrous iron. The author considers⁶ that so-called "leptochlorite" differs from ordinary chlorite only because its ferrous iron has been more or less oxidized to the ferric state. Dschang⁷ has shown that such a change can be

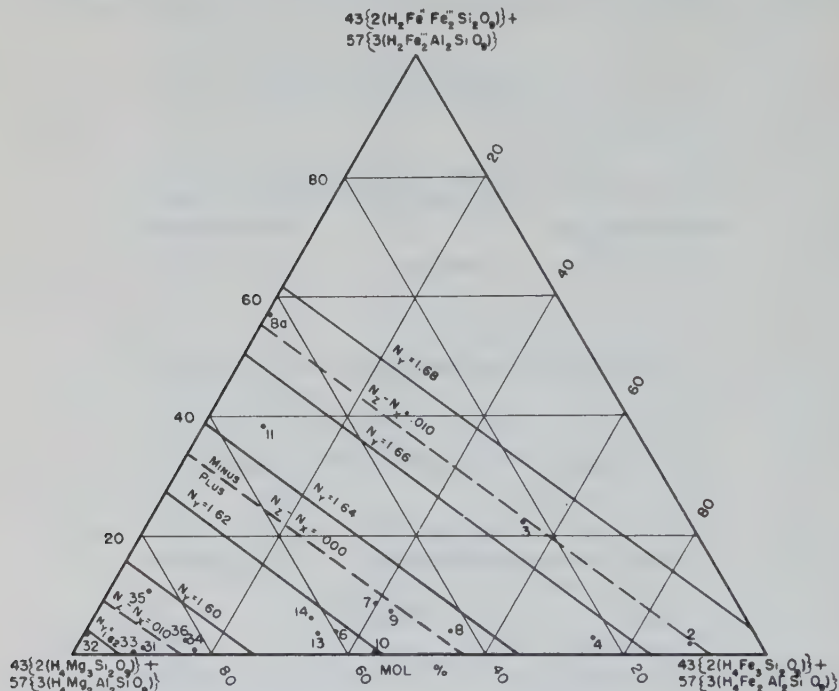


FIG. 4

produced artificially. In general the change raises the indices of refraction and increases the birefringence; it may cause a change in the optic sign from positive to negative. The effects upon certain types of chlorite⁶ are shown approximately in Fig. 4.

Johnsen⁸ proved that a crystal of sphene containing only 0.5 per cent of FeO changes from yellow to deep brown when the iron is oxidized by

⁵ Hutton (*loc. cit.*) based a similar diagram on weight percentage of divalent and trivalent bases.

⁶ Winchell, A. N., *Am. Mineral.*, **21**, 642 (1936).

⁷ Dschang, G. L., *Chem. Erde*, **6**, 416 (1931).

⁸ Johnsen, A., *N. Jahrb. Mineral., Bl. Bd.*, **48**, 136 (1923).

heating in air and reverts to the original condition when next heated in hydrogen. This was doubtless due to the presence of a little hydroxyl in the original crystal.

In summary, it is evident that oxidation *of* minerals is accomplished by addition of oxygen and complete destruction of the original mineral, whereas oxidation *in* minerals is accomplished by loss of hydrogen but with no addition of oxygen and no destruction nor even any considerable change in the structure or properties of the original mineral.

NONTRONITE IN THE COLUMBIA RIVER REGION*

VICTOR T. ALLEN AND VERNON E. SCHEID,

Geological Survey, U. S. Department of the Interior, Washington, D. C.

ABSTRACT

New occurrences of nontronite have been discovered in Washington, Idaho, and Oregon. The nontronite has formed by the weathering of basaltic glass, palagonite, iddingsite, and augite under conditions of poor drainage in the presence of alkalies, magnesium and probably ferrous iron. Under conditions of thorough drainage in the presence of neutral or slightly acid solutions kaolinite and halloysite are formed from plagioclase feldspar, while nontronite migrates and fills vesicles as well as cracks ranging from a fraction of an inch to six inches in width. Chemical analyses and optical data are given for three new nontronites and for two materials connected with the formation of nontronite.

INTRODUCTION

Several new occurrences of nontronite in Washington, Idaho, and Oregon have been studied during the investigation of high-alumina clays by the Geological Survey, U. S. Department of the Interior. In the Columbia River region nontronite is associated with altered basaltic rocks, pillow lavas, tuffs and palagonite, indicating a genetic connection between the weathering of these materials and the formation of nontronite. In the Excelsior district the study of cores obtained during a co-operative drilling project with the Bureau of Mines, U. S. Department of the Interior, revealed a significant variation in the weathering products of basaltic rocks with depth. At Excelsior, Colfax and Garfield, Washington, nontronite of exceptional purity was collected from veins, ranging from a fraction of an inch to six inches in width. Petrographic and chemical studies of nontronite and the associated rocks indicated that the nontronite is formed chiefly by the weathering of basaltic glass and that palagonite is an intermediate product in its alteration. This observation led the writers to examine the published information on palagonite.

PREVIOUS WORK ON PALAGONITE

The selected references that are reviewed here summarize the previous studies of palagonite and its alteration.

Von Waltershausen (1845) applied the name palagonite to the material forming the brown groundmass of a tuff from Palagonia, Val di Noto, Sicily. He (1847) found palagonite typically developed in the massive tuffs of Iceland.

* Published by permission of the Director, Geological Survey, U. S. Department of the Interior.

Fermor (1925) concluded that the brown and orange varieties of palagonite in the Deccan trap of Bhusawal, Bombay Presidency, are identical with chlorophaeite and that the green variety, when anisotropic, is probably delessite or celadonite.

Peacock (1926) recorded the chemical composition of basaltic glass from Iceland, for which he used the term "sideromelane," and gave the index of refraction of eight Icelandic "sideromelanes" ranging from 1.604 to 1.615. He considered that the "sideromelane" resulted from chilling by Pleistocene ice sheets on the products of sub-glacial volcanoes. By hydration, oxidation of iron and partial loss of lime and soda, "sideromelane" changed to a yellow material that is isotropic (gel-palagonite) or obscurely fibrous and birefracting (fibro-palagonite). The index of refraction of his palagonites ranged from 1.48 to 1.52 and the water content of five palagonite rocks from 14.20 to 24.40 per cent. He concluded that palagonite is unstable and tends to crystallize with a partial loss of water into chlorite and zeolites.

Peacock and Fuller (1928) described chlorophaeite, "sideromelane" and palagonite from the Columbia River plateau. They urged that the name chlorophaeite be extended to cover all hydrous, amorphous, pitch-like materials of deuteric origin in basalts and dolerites; that "sideromelane" be continued as a specific name for ideal basaltic glass formed under conditions of specially rapid cooling; and that palagonite should be restricted to its original significance, namely the hydration product of sideromelane by water or water vapor of exotic origin. Rapid cooling that would produce sideromelane results when a lava is extruded into the sea or a lake. Palagonitization of tuffs which involves hydration of sideromelane, extensive oxidation of its iron and loss of some lime and soda is here attributed to the steam generated in the quenching of the extruded material. At the vents steam charged with acidic volatiles is considered responsible for the alteration of sideromelane fragments to a turgid-gray iron-free material with an index of refraction of 1.45. This material which is considered to have lost iron and perhaps other bases by solution would be included under the term palagonite as used by these writers.

Powers (1932) observed that the chemical decomposition of basaltic ash in Hawaii proceeds more rapidly than that of basaltic lava. He believes this is connected with the unstable nature of the glass particles composing the ash and with the rapidity with which basaltic glass changes to palagonite. He was unable to determine all the secondary decomposition products of the glass, but he recognized the presence of palagonite and undetermined materials of colloidal dimensions. Pertinent quotations

from this significant paper seem advisable, since it is not widely available for reference:

"The fundamental cause for the difference in the amount of chemical decomposition of the ash and lava lies in the fact that the former is an unstable glass and the latter an aggregate of crystals. The ash particles are in reality a liquid, undercooled far below the crystallization temperatures of the constituent compounds. The glass thus is in a highly unstable physical state and will rapidly break down to more stable forms under atmospheric conditions of temperature, pressure and moisture. The first stage in this breakdown is a complete alteration of the original glass to palagonite. This is a yellow isotropic substance which has essentially the same chemical composition as the primary basaltic glass, that is, the total composition of the basaltic magma—except that most of the iron is oxidized and water of hydration is added. Insufficient work has been done to determine the exact identity of all the secondary products resulting from the decomposition of the original glass. Much of the material large enough in particle size to be microscopically identified is definitely palagonite. On the other hand, a very considerable portion is of colloidal dimension and highly hydrated and can not be identified by ordinary petrographic methods. It is significant in this connection, that in the various localities where ash deposits exist in the Hawaiian Islands the decomposition products are always of the same general character as to color and physical properties. This would seem to indicate that this yellow-brown alteration product is fairly definite in composition and also rather stable in character.

"The slow cooling of lava gives an opportunity for the constituents of the liquid to crystallize as minerals of fairly definite chemical composition. The bulk of the crystalline constituents consists of pyroxene, a metasilicate of calcium, iron, and magnesium; plagioclase feldspar, a polysilicate of aluminum, calcium and sodium (and a trace of potassium); and olivine, an orthosilicate of magnesium and iron. Although much of the surface lava in Kona is older than the ash, it shows practically no decomposition. Even the very permeable scoria of an aa flow, which is largely crystalline material, yields very slowly to the alteration processes. A striking example of the differences in weathering of glassy and crystalline material under equal climatic conditions is found in the ash beds of Tantalus and Punchbowl on Oahu. Some layers are completely altered to yellow, but other layers and pockets are black and untouched by weathering. The altered beds were made up of fine particles of basaltic glass whereas the black unaltered material consists of coarse particles of partly crystalline basaltic rock. . . .

"Microscopic examination of the very fine sand and silt fractions of the pure ash samples shows that they are composed of three chief types of material—black particles of magnetite which formed within the basaltic glass and remained unaltered during its decomposition; rounded yellow particles of palagonite, the decomposition product of basaltic glass; and undecomposed, angular fragments of minerals, chiefly olivine and feldspar, which were present as crystals in the magma from which the ash was formed. The absence of any undecomposed particles of glass and the lack of decomposition of the mineral fragments bear out the conclusion that the soils of Kona are in the main the result of decomposition of basaltic glass, although it is probable that in the wetter belts the very fine particles of scoria have undergone a certain amount of decomposition."

Hoppe (1941) carried on experiments on the decomposition of basaltic glass by waters of varying pH values to determine the conditions of formation of palagonite. He concluded that decomposition was probably

due to the action of water vapor at elevated temperature, perhaps approximately 200°.

In a study of some altered palagonite tuffs from Jamaica, Raw (1943) recognized that the palagonite originated from basaltic glass, that "sideromelane" is inherently unstable, and that palagonite, which is the product of the action of water on it, is essentially chlorite. He considered that palagonitization is a slow process, and before it is much advanced, the rock spaces are filled with low-grade chlorite followed by a zeolite. Two types of chlorite, belonging to two stages and differing in orientation, are described. Deformation may raise the grade of both these chlorites and change palagonite tuffs to chlorite schists and chlorite-albite schists.

Ross and Hendricks (1945) suggested that the beidellite-nontronite collected by Edward Sampson from material lying between two basalt flows near Spokane, Washington, is an alteration product of basaltic volcanic glass. They remark that it would be interesting to know if the volcanic glass first altered to palagonite as observed by Powers in Hawaii and later assumed the crystalline form.

COMPOSITION AND OPTICAL PROPERTIES OF NONTRONITE

Analyses of the nontronites, which were collected from the veins at Excelsior, Colfax, and Garfield are shown in Table 1 along with an un-

TABLE 1. NONTRONITE ANALYSES

	1 Excelsior, Wash.	2 Colfax, Wash.	3 Garfield, Wash.	4 Dale Co., Ala.	5 Sandy Ridge, N. C.	6 Spokane, Wash.	7 Spokane, Wash.
SiO ₂	41.63	40.25	40.24	40.93	41.38	40.72	46.06
Al ₂ O ₃	8.69	5.50	4.94	6.33	9.84	4.96	12.22
Fe ₂ O ₃	25.99	29.44	30.17	30.07	27.47	29.57	18.54
FeO		none	none	.11	tr.?	.71	.28
MgO	.33	.53	.39	.80	tr.?	.74	1.62
CaO	1.78	2.29	2.36	.23	tr.?	1.98	1.66
Na ₂ O	.22	none	none	none	tr.?		
K ₂ O	.32	none	none	none			
H ₂ O—	10.67	15.09	15.29	14.04	12.10	15.46	} 17.26
H ₂ O+	9.91	7.25	6.79	7.76	9.25	6.66	
TiO ₂	tr.	.03	.02	.04	tr.?	.02	.84
Total	99.54	100.38	100.20	100.31	100.04	100.82	98.48
Analyst	J. Husted	N. Davidson	N. Davidson	W. Brannock	R. C. Wells	J. Fairchild	E. Shannon
Collector	Allen and Scheid			F. MacNeil	J. Shaffer	—	E. Sampson

published analysis of nontronite from Dale County, Alabama, and three published analyses. C. S. Ross (1927, p. 148), Larsen and Steiger (1928), and others (Ross and Kerr (1931)) have recognized that nontronite is the

ferric oxide end member of an isomorphous series in which beidellite is the aluminous end member. Gruner (1935) has emphasized that the similarity in structure of nontronite, beidellite and montmorillonite as shown by x-ray patterns indicates an isomorphous series that is completely miscible.

LOCATION OF SAMPLES LISTED IN TABLES 1 AND 2

- (1) Excelsior clay deposit, Spokane County, about 12 miles southeast of Spokane, Washington, SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 16, T. 24 N., R. 44 E. Veins of yellow green clay associated with weathered pillow lava.
- (2) Along road cut on U. S. Highway 195, north of Colfax, Whitman County, Washington, SE $\frac{1}{4}$ sec. 35, T. 17 N., R. 43 E. Veins of yellow green clay associated with weathered basalt.
- (3) Along road cut on Palouse Highway, 1 mile south of Garfield, Whitman County, Washington, sec. 4, T. 17 N., R. 45 E. Veins of yellow clay 1" to 6" wide associated with weathered basalts.
- (4) Along a road cut in the north center of sec. 18, T. 7 N., R. 24 E., about 3 miles south-east of Ariton, Dale County, Alabama. Unpublished analysis of a sample submitted by F. S. MacNeil. Nontronite occurs as nodules in a glauconite sand in the Hatchetigbee formation of Eocene age.
- (5) Sandy Ridge, N. C. Veinlets 5 to 10 mm. wide in schist. Collected by J. B. E. Shaffer of Sandy Ridge. Color, clear dull green. Wells (1937, p. 109).
- (6) About 17 miles southeast of Spokane, Washington, in SW $\frac{1}{4}$ sec. 5, T. 23 N., R. 45 E. Relations unknown. Color, clear dull yellowish green. (Ross and Hendricks (1945, p. 32).)
- (7) Spokane, Washington. Nontronite-beidellite of yellowish citrine color lying between two basalt flows. Collected by Edward Sampson. Ross and Shannon (1936, p. 94).

In the six nontronites listed in Table 1, the silica varies between 40.24 and 41.63 per cent; ferric oxide varies between 25.99 and 30.17 per cent. Alumina depends on the amount of the beidellite molecule present and varies between 4.94 and 9.84 per cent. No. 7 is the nontronite-beidellite of Ross and Shannon in which alumina is about equal molecularly to the ferric oxide.

TABLE 2. OPTICAL PROPERTIES OF NONTRONITE

Sample No.	Locality	Indices of Refraction		Birefringence $\gamma - \alpha$	Optical Character
		α	γ		
1	Excelsior, Wash.	1.572	1.615	.043	negative
2	Colfax, Wash.	1.580	1.625	.045	negative
3	Garfield, Wash.	1.598	1.643	.045	negative
4	Dale County, Ala.	1.585	1.625	.040	negative
5	Sandy Ridge, N. C.	1.590	1.630	.040	negative
6	Spokane, Wash.	1.585	1.625	.040	negative
7	Spokane, Wash.	1.568	1.606	.038	negative

FORMULAS OF NONTRONITES

Sample No.	Octahedral Coordination	Tetrahedral Coordination
1	(Al _{.29} Fe ^{'''} _{1.66} Mg _{.08})	(Al _{.61} Si _{3.49}) (Ca _{.32} Na _{.02} K _{.03}) O ₁₀ (OH) ₂
2	(Al _{.06} Fe ^{'''} _{1.92} Mg _{.70})	(Al _{.60} Si _{3.60}) (Ca _{.43}) O ₁₀ (OH) ₂
3	(Al _{.02} Fe ^{'''} _{1.97} Mg _{.50})	(Al _{.60} Si _{3.60}) (Ca _{.44}) O ₁₀ (OH) ₂
4	(Al _{.07} Fe ^{'''} _{1.92} Fe ^{''} _{.01} Mg _{.20})	(Al _{.62} Si _{3.48}) (Ca _{.08} H _{.25}) O ₁₀ (OH) ₂
5	(Al _{.35} Fe ^{'''} _{1.70})	(Al _{.58} Si _{3.42}) (Ca _{.00} H _{.26}) O ₁₀ (OH) ₂
6	(Al _{.06} Fe ^{'''} _{1.94} Fe ^{''} _{.05} Mg _{.10})	(Al _{.46} Si _{3.55}) (Ca _{.18}) O ₁₀ (OH) ₂
7	(Al _{.77} Fe ^{'''} _{1.10} Fe ^{''} _{.02} Mg _{.19})	(Al _{.37} Si _{3.63}) (Ca _{.28}) O ₁₀ (OH) ₂

In Table 2 a formula representing $\frac{1}{2}$ the unit cell is given for each nontronite according to the method of Ross and Hendricks (1945, pp. 41-45) in which the aluminum+silicon ions in tetrahedral coordination must equal 4 and the O+(OH) ions must equal 12. In the nontronites from Washington the replaceable ion is Ca, and in those from Alabama and North Carolina, Nos. 4 and 5 respectively, hydrogen is present, making them acid clays. Small amounts of magnesium are significant, as magnesium plays an important role in the synthesis of beidellite, montmorillonite and possibly nontronite (Ewell and Insley, 1935; Noll, 1936).

In these samples the indices of refraction are highest for the nontronites with the highest ferric iron. No. 3 from Garfield has the highest indices of refraction and most nearly approximates a pure iron-end member, having 1.97 ferric iron and only .02 alumina proxying ferric iron in octahedral coordination. The values for the indices of refraction given in Table 2 were determined on prepared mineral strips that were immersed for several weeks in closed vials, each containing an oil of a known index of refraction (Ross and Hendricks, 1945, p. 54). The values determined on samples with occluded air, as they came from the field, are somewhat lower.

FIELD RELATIONS OF THE NONTRONITE

The field relations indicate that most of the nontronite in the Columbia River plateau has been produced by weathering of basaltic glass that originally composed basaltic vitric tuffs, the glassy skin of pillow lavas and the glassy groundmass of basaltic lavas. The nontronite from this source and from the weathering of augite and iddingsite migrated into cracks, ranging from a fraction of an inch to 6 inches wide, like those at Excelsior, Colfax, and Garfield. Other nontronite veins occur along the U.P.R.R. cut at the old Lockwood siding, 1 mile west of Manito, Wash-

ington. These were probably the source of the material submitted to Dr. C. S. Ross and listed as No. 6, Tables 1 and 2.

In the Excelsior district (NE. $\frac{1}{4}$ sec. 8, T. 23 N., R. 45 E.) cores 5 inches in diameter and one foot long were composed wholly of massive yellow-green nontronite. Similar masses 1 to 4 inches in diameter were found in other drill holes at the Excelsior deposit and at the Olson clay deposit, about 8 miles northeast of Troy, Latah County, Idaho (secs. 19, 30, T. 40 N., R. 2 W.). The textures of this nontronite in thin section indicate that the original rock was a vitric tuff, in which some of the glassy fragments had a pumiceous texture. At Colfax the glassy material of a vitric crystal tuff is altered to nontronite and to palagonite (Fig. 6). The relations clearly indicate that large masses and perhaps beds of nontronite have been formed from the fragments of basaltic glass that are interlayered with basalt flows.

The nontronite at Excelsior (No. 1, Tables 1 and 2) occurs at the margins of pillows and in veins cutting weathered pillow basalt. It was probably formed from the glassy skin and vesicular crust that was produced by rapid cooling of the lava induced by contact with water or a moisture-laden medium, or from the glassy fragments that were shattered from the outer rim of the pillows (Fenner 1910, p. 103; Lewis 1914, p. 650). Along a road-cut on highway 99 W. about 2 miles south of Portland, Oregon, brown nontronite-beidellite is associated with palagonite and opal at the rim of pillow lavas (Fig. 5). Yellow-green nontronite fills vesicles in the basaltic lava at this locality.

Along a road-cut about 800 feet west of Valleyford, Spokane County, Washington, nontronite has formed from the glassy groundmass of a basalt in which the plagioclase and augite have remained fresh (Fig. 2). Yellow green nontronite fills vesicles in the basalt. The combined effect of both types of nontronite is to give to the hand specimen of the rock a yellowish-green color.

At Marion, Oregon, palagonite (No. 1, Table 3) occurs in irregular veins around pillow lava in a manner similar to that of the nontronite at Excelsior, Washington. The change of basaltic glass, such as No. 3, Table 3, to palagonite involves extensive hydration, almost complete oxidation of iron, and loss of some silica, alumina, calcium, magnesium, and alkalis. According to Peacock and Fuller (1928, p. 376) this change is accomplished by the steam generated in the quenching of the extruded lava. Powers (1932, p. 9) in his study of Hawaiian soils attributed palagonitization to weathering of basaltic glass in the moist, warm climate of the Hawaiian Islands.

The "basaltic glass" found by Diller (No. 4, Table 3) at Rooster Rock, 25 miles east of Portland, Oregon, might well be termed palagonite, since almost all the iron is present as Fe_2O_3 and the total water is 19.46 per cent. Diller recognized the relation of the material to palagonite and its altered condition. His description of the material and its occurrence follows:

"The whole mass of the cliffs when seen from the railroad is more or less distinctly stratified, but the layers are large and massive, so that the stratification is not conspicuous. When examined in detail the strata are found to be made up entirely of fragmental volcanic material forming what is technically called tuff, or, in this case, basalt tuff, on account of the basaltic character of the fragments. Such material is sometimes called palagonite tuff, from its occurrence in Palagonia, Sicily.

"The layers are composed chiefly and often wholly of a substance ranging in color from light to dark brown and black, and in luster from dull glassy to pitch like and resinous. For the most part the rock is decidedly fragmental. It contains fragments of dark basalt from the size of a pea to blocks several feet in diameter. When broken, these pieces are often seen to have a black pitchy border, as if once enveloped by a molten mass.

"Weathering brings out the fragmental structure on the surface of the glassy portions, but this is still more evident in a thin section of the rock where the dark brown completely isotropic glass fragments full of small lath-shaped crystals of plagioclase feldspar, with fewer crystals of augite and grains of olivine, like those of the basalt, are encompassed and bound together by a lighter brown matrix like gelatin, which has fibrous polarization.

"Locally among the distinctly fragmental layers are sheets of the yellowish-brown waxy-lustered material which in thin section is found to be an altered jellylike substance containing crystal fragments of plagioclase, augite, and olivine like those in the basalt of the large fragments and flows in the cliffs, and it is evident that the whole mass is from a volcano erupting basalt."

This locality was not visited by the writers, but the description of waxy-lustered material of various colors suggests the material at Marion and that occurring two miles south of Portland, which changed color with loss of water. J. M. Axelrod of the Geological Survey, U. S. Department of the Interior, could detect no difference in the x -ray patterns of different colored parts, all of which gave the x -ray patterns of nontronite and opal.

The change of palagonite to nontronite with 40 or 41 per cent silica and 26 to 30 per cent ferric oxide would generally require some further loss of silica, alumina, calcium, magnesium and alkalis. Opal associated with palagonite (No. 1, Table 3), with nontronite (No. 2, Table 3), with altered pillow lavas south of Portland (Fig. 5) and east of Pullman, Washington, is evidence that intensive chemical change has taken place.

Other occurrences of nontronite are known in the Columbia River region where the source material of the nontronite is not so definitely dis-

TABLE 3

	1	2	3	4	5	6	7
	Palagonite Containing Opal. Marion, Ore.	Opal, White Earthy Veins in Nontronite. Colfax, Wash.	Basaltic Glass (Sidero- melane). Douglas county, Wash.	Palagonite Tuff 25 Miles East of Portland, Ore.	Palagonite Rock. South Pacific	Palagonite Rock. Iceland	Iddingsite. Average of 7 Analyses
SiO ₂	69.39	92.69	51.30	40.89	44.73	35.34	39.11
Al ₂ O ₃	2.53	.64	18.54	10.41	16.26	11.15	3.29
Fe ₂ O ₃	12.70	1.91	0.26	15.00	14.57	10.28	31.49
FeO	none	none	11.21	0.07	nd.	2.19	.96
MgO	.59	.05	4.03	3.76	2.23	6.52	8.05
CaO	1.09	.44	8.55	5.18	1.88	7.01	2.28
Na ₂ O	none	none	2.83	0.47	4.50	0.16	
K ₂ O	none	none	1.05	0.53	4.02	0.19	
H ₂ O—	8.79	1.75	tr.	9.14		15.50	7.78
H ₂ O+	4.67	2.72	0.30	10.32	9.56	8.90	8.49
TiO ₂	.04	.04	1.40	3.37		2.10	.18
MnO	tr.	none	0.35	0.90	2.89	0.22	
Others			0.05	.56		.31	
Total	99.80	100.24	99.87	100.60	100.64	99.87	101.63
Analyst	N. Davidson	N. Davidson	Herdsmen	G. Steiger	A. Renard	Herdsmen	Shannon
Collector	V. Allen	V. Scheid	Fuller	Diller	Murray	Peacock	Ross

LOCATION OF SAMPLES LISTED IN TABLE 3

- (1) Palagonite containing opal occurs in veins around pillow lava along S.P.R.R. cut near station, Marion, Marion County, Oregon.
- (2) White, earthy opal in center of 2 inch nontronite vein (Tables 1 and 2, No. 2). Along road cut on U. S. Highway 195, north of Colfax, Whitman County, Washington, SE $\frac{1}{4}$ sec. 35, T. 17 N., R. 43 E.
- (3) Basaltic glass (sideromelane) from the lake-quenched nose of a flow at Columbia River, 3 miles south of Moses Coulee, Douglas County, Washington. Peacock and Fuller (1928, p. 371).
- (4) Palagonite tuff. Near Rooster Rock, about 25 miles east of Portland, Oregon, Diller (1905, p. 345).
- (5) Palagonite, South Pacific. Murray and Renard (1891, p. 307).
- (6) Palagonite rock, Iceland, Peacock (1926, p. 66).
- (7) Iddingsite, average of 7 analyses. Ross and Shannon (1925, p. 16).

played. In the Eola Hills, west of Salem, Oregon, nontronite and halloysite fill a vein $\frac{3}{4}$ inch thick which cuts the Stayton lavas (Allen, 1945, p. 269). Green nontronite cements andesitic detritus occurring along the new Ostrander logging road, about three miles southeast of Molalla, Oregon (Allen, 1945, p. 269). The nontronite is cracked and pale-green nontronite fills the cracks in the sedimentary nontronite. This relationship at Molalla suggests that the cracks were formed when the clay dried

and that pale-green nontronite was deposited in the cracks when the clay was again saturated with water. In the clay deposit near Castle Rock, Cowlitz County, Washington, nontronite occurs in detrital sedimentary rocks (Allen and Nichols, 1943; Allen, 1946). At Salem, Molalla and Castle Rock basaltic lavas are present in the same section as the nontronite but a close relationship between the altered glass or ferromagnesian minerals of the basalts and the nontronite at these localities has not been demonstrated thus far.

PETROGRAPHIC OBSERVATIONS AND THEIR SIGNIFICANCE

Petrographic study has contributed additional information. The glassy groundmass of some basalts contains rod-like inclusions of augite or other ferromagnesian minerals that may have a fan-like arrangement (Fenner 1910, p. 100). In the Excelsior district basaltic glass alters to nontronite that retains rods of augite (Figs. 1, 2, 4). Basaltic glass is less stable than the augite-rods it encloses or the large grains of fresh augite in the same specimen.

In Fig. 1, iddingsite crystals are embayed by and partially altered to nontronite. As basaltic glass is also partially altered to nontronite in this specimen, iddingsite was almost as susceptible to alteration as was the basaltic glass. If one compares the composition of iddingsite (No. 7, Table 3) and nontronite (Table 1), it is evident that iddingsite needs only to lose some magnesium and to gain additional water to approach nontronite in composition. Iddingsite with a definite crystalline structure would be more apt to resist alteration and reorganization than amorphous material, such as a basaltic glass, having a similar composition.

In Fig. 2 nontronite has formed from basaltic glass, whereas augite, plagioclase and ilmenite have remained fresh. Nontronite fills vesicles and openings in the lava. Also, irregular masses of zoned nontronite have resulted from the alteration of the glassy groundmass, and small spherical nodules may have resulted from the resorption of olivine, as suggested by Fenner (1910, p. 102), and its subsequent alteration. Some of the nontronite varies in color with the amount of ferric oxide present and forms varied colored zones within a single area. If all the zones were composed of members of the nontronite-beidellite series one would expect the dark zones to have more ferric iron and higher indices of refraction than the light colored zones. In a thin section from Colfax a dark zone in the center had lower indices of refraction than those of the light colored material surrounding it, and this suggested the dark zone was composed of the magnesium member of the montmorillonite group, saponite (Ross, 1945). Numerous immersions were made of the clay minerals from the vesicles but the presence of saponite could not be substantiated. All the grains

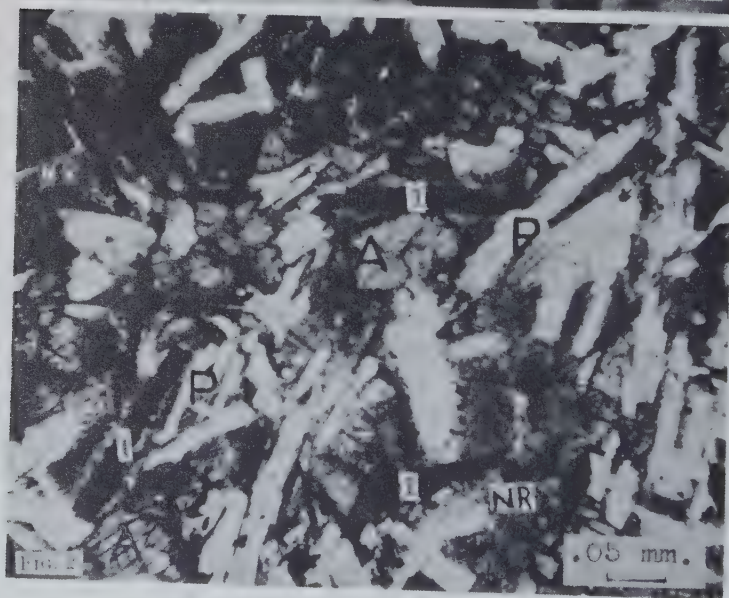
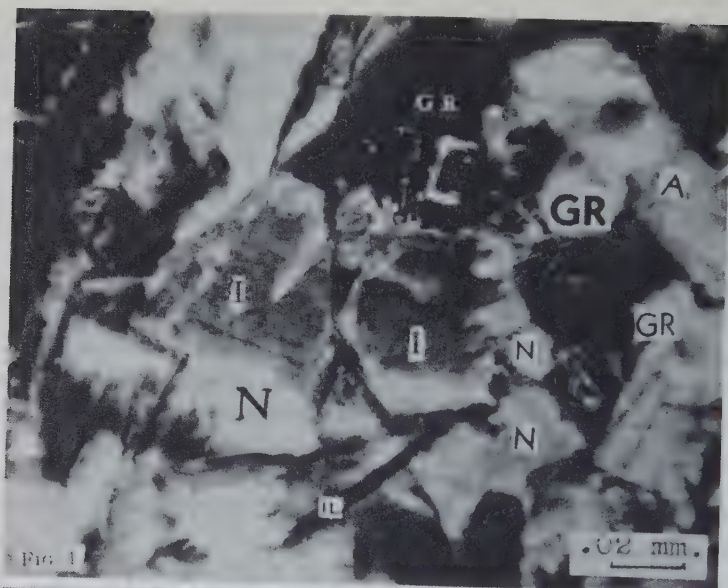


FIG. 1. Nontronite (N) has formed from the glassy groundmass and from iddingsite (I). Black (GR) is basaltic glass containing rods of augite. Augite (A) is fresh. IL is ilmenite. Excelsior, Spokane County, Washington.

FIG. 2. Nontronite (NR) contains rods of augite once present in basaltic glass. Nontronite fills vesicles (NV), some of which are zoned (left near center). Augite (A) is unaltered. Plagioclase (P) is unaltered. I is ilmenite. Valleyford, Spokane County, Washington.

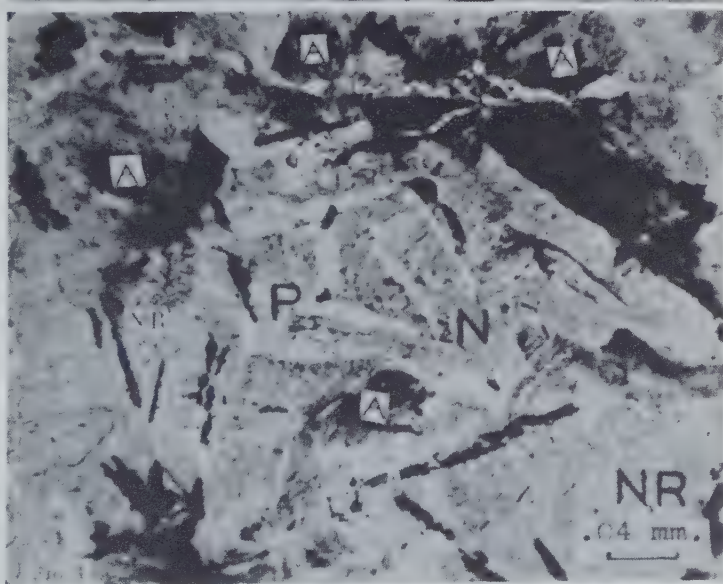
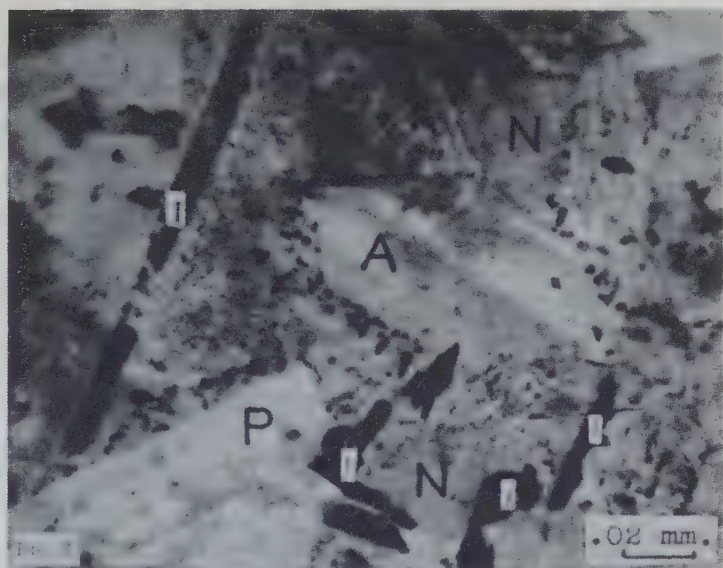


FIG. 3. Augite crystal (A) and glassy groundmass (N) are altered to nontronite. Plagioclase (P) is fresh. I is ilmenite. Excelsior, Spokane County, Washington.

FIG. 4. Nontronite (NR) contains rods of augite. Augite (A) is altered to nontronite. Calcic core of plagioclase (P) is altered to nontronite. I is ilmenite. Excelsior, Spokane County, Washington.

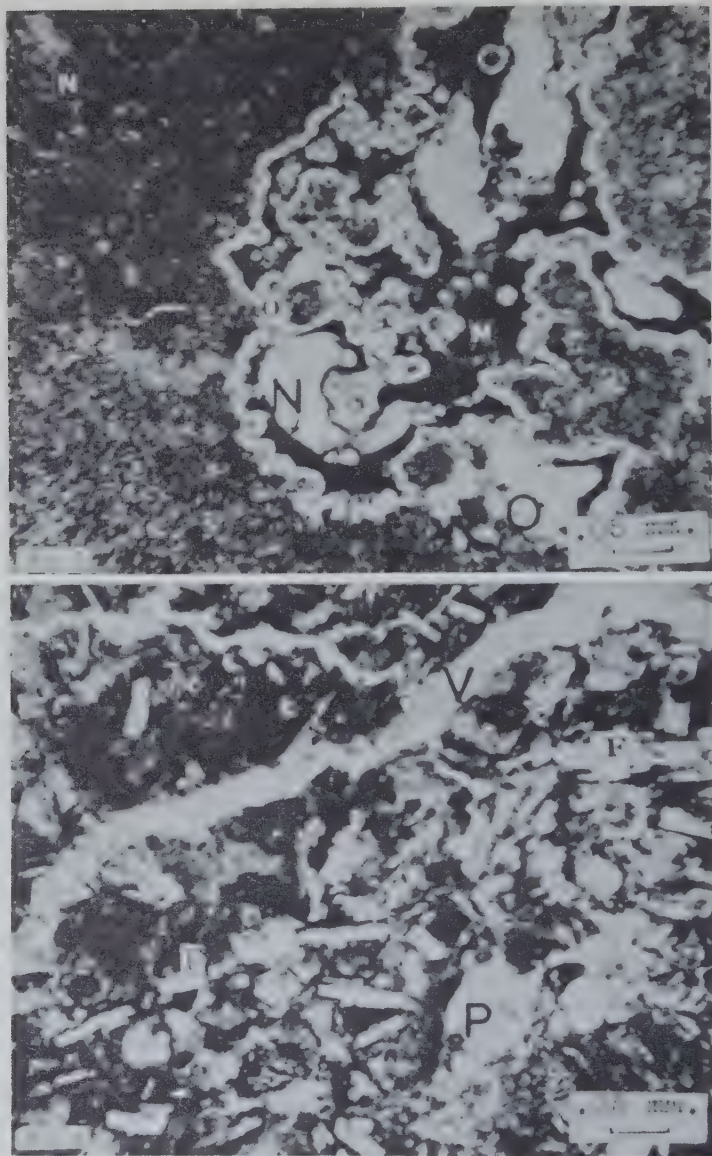


FIG. 5. Palagonite is altered to nontronite (N). Opal (O) and nontronite (N, black) fill an open cavity. Some nontronite has broken loose in making the thin section, leaving white areas. Around pillow lava, at a road cut on Highway 99 W, 2 miles south of Portland, Oregon.

FIG. 6. P is yellow palagonite; dark areas are altered and iron stained palagonite. V is a vein of nontronite. Lath shaped grains (F) are plagioclase altered to kaolinite. Colfax, Whitman County, Washington.

isolated and measured had indices of refraction within the range of those for the nontronite-beidellite series. The small amounts of magnesium in the nontronite analyses listed in Table 1 show that only limited amounts of saponite could be present in those samples and, it appears likely that magnesium ions proxy aluminum ions in octahedral positions in the analyzed samples.

In Fig. 3, a large crystal of augite and the glassy groundmass of a basalt have altered to nontronite, whereas plagioclase and ilmenite have remained fresh.

In Fig. 4, the glassy groundmass containing fan-like inclusions of augite and large augite grains are altered to nontronite. The calcic core of plagioclase is altered to nontronite, but not the sodic rim. The materials illustrated in Figs. 1 to 4 can be arranged in a series, each member of which has increased resistance to weathering, as: (1) basaltic glass, (2) iddingsite, (3) augite, (4) plagioclase, (5) ilmenite. Some residual basaltic clays in the Excelsior district contain 7 per cent TiO_2 , which is present mainly as ilmenite.

The ease with which basaltic glass alters to nontronite depends first on its chemical composition. The curves of W. O. George (1924) can be used to estimate the composition of a volcanic glass from its index of refraction, which varies inversely as the silica content. Peacock (1926) recorded that the index of refraction of 8 Icelandic basaltic glasses varied between 1.604 and 1.615, and his analyzed specimen of Icelandic basaltic glass contained 46 per cent SiO_2 . Fuller's determinations of the index of refraction of basaltic glasses from Washington (Peacock and Fuller, 1928) varied between 1.583 and 1.597. His analyzed sample (Table 3, No. 3) contained 51 per cent silica and had an index of refraction of 1.583. Thus, the composition of basaltic glass is known to vary. Other factors being equal, the basaltic glass with the lowest silica would be the most unstable.

Secondly, the ease of alteration of basaltic glass varies with its texture. A massive, glassy lava flow resists alteration, whereas the fragmental texture of a glassy tuff allows the ready percolation of reacting solutions. In the Excelsior district tuffs are more completely altered to nontronite than the associated lava flows at the same depth. Powers (1932) has observed that glassy tuffs in Hawaii weather more rapidly than lava flows characterized by crystalline materials.

Thirdly, the ease of alteration of basaltic glass to nontronite varies with the conditions and the composition of the reacting solutions. The formation of nontronite is favored by conditions of poor drainage and by the presence of alkalis, alkaline earths, magnesium, and probably ferrous iron.

Statements appear in the literature that palagonite is unstable and alters to chlorite. It was observed that heating certain specimens from Excelsior, Washington, during the preparation of thin sections caused some fragments with a glassy texture to turn green. Their mean index of refraction is within the range for chlorites, but also is within the range for intermediate members of the nontronite-beidellite series. *X*-ray patterns by J. M. Axelrod indicated the absence of chlorite and the presence of nontronite-beidellite. The apparent low birefringence of these fragments is probably caused by their fine-grained nature and incipient development of the nontronite. In the light of the experience with palagonite from Washington and Oregon it seems that reported occurrences of chlorite in palagonite at other localities should be reexamined using *x*-ray and other methods.

The *x*-ray pattern of the palagonite occurring around pillow lava at Marion, Oregon (Table 3, No. 1), is reported by J. M. Axelrod to indicate opal and nontronite. In thin section areas of opal are clearly visible, and there are also present materials with indices of refraction that vary in different parts of the section. Some of these have a mean index of refraction of 1.525, and others have moderate birefringence and a mean index of refraction (with occluded air) of 1.555 that may be nontronite-beidellite.

The massive palagonite around pillow lava, 2 miles south of Portland, Oregon, gave an *x*-ray pattern that indicated opal and a member of the nontronite-beidellite series. A green clay mineral that is probably nontronite-beidellite can be seen in the thin section of the massive portion (Fig. 5). Opal lines cavities in the massive portion and a brown nontronite-beidellite having a mean index of refraction of 1.565 (with occluded air) fills the center of the former openings. Reddish-brown common opal with an index of refraction of 1.445 forms lumps 1 to 3 inches across at this locality. Along a road cut on highway 3, at the east edge of Pullman, Washington, yellow common opal with an index of refraction of 1.455 forms similar lumps around pillow lava.

White earthy opal (Table 3, No. 2) forms a pod within a 2-inch nontronite vein at Colfax and the center of this pod is filled with nontronite. This earthy opal has an index of refraction of 1.455 and it gave no *x*-ray pattern, being truly amorphous.

The separation of silica from the glassy skin of pillow lava and from palagonite is indicated at these localities. The experiments of Lovering (1923) suggest that alkalies and magnesium bicarbonate are effective agents in removing silica. These agents were present in the original basaltic rocks and were partially or wholly removed along with silica during the weathering process.

Another locality where somewhat similar relations have been observed is Umnak Island, Alaska, which attracted the attention of scientists because volcanic activity was in progress during 1945 within 65 miles of Dutch Harbor. Lieutenant R. E. Wilcox collected volcanic material from the outer slopes of the unnamed caldera that occupies the northeastern part of Umnak Island. Dr. Clarence S. Ross, of the Geological Survey, U. S. Department of the Interior, studied the material and kindly prepared the following statement for inclusion in this paper:

"One specimen represented fresh unaltered basaltic glass, which is nearly colorless in thin section. Another specimen from the same eruption contains alteration products of the same type of glass. Part of it is a yellow-brown palagonite in which hydration and partial oxidation have produced an isotropic material with a lower index of refraction than that of the basaltic glass from which it was derived. Most of the material, however, has undergone further alteration to a very fine-grained aggregate that is dull green in color. This material is anisotropic under strong illumination, although it is so exceedingly fine grained that this evidence of its crystallinity would be recognizable only in a material with moderately high birefringence. These relations indicate that the dull green final product of the alteration of this basaltic glass is nontronite."

ORIGIN AND MIGRATION OF NONTRONITE

Several facts suggest that two different sets of weathering conditions have prevailed in the Columbia River region. In the Excelsior district nontronite is present in the lower poorly drained part of the profile of weathering, where the stagnant alkaline solutions contain magnesium. Here, plagioclase, basaltic glass and iddingsite are altered to nontronite. In the upper well-drained part of the profile revealed in the same drill-holes plagioclase is altered to kaolinite or halloysite and iddingsite resists alteration. Along a road cut on highway 8 near Nora, 3 miles east of Troy (NW. $\frac{1}{4}$, S. 1, T. 39 N., R. 3 W.), Latah County, Idaho, unaltered iddingsite occurs in a weathered basalt in which the plagioclase is completely altered to kaolinite. In the Mehama district, Marion County, Oregon, euhedral plagioclase phenocrysts with relict twinning are completely altered to kaolinite but the iddingsite in this volcanic rock is unaltered. Thorough leaching by neutral or slightly acid solutions that produces kaolinite from plagioclase did not favor the formation of nontronite from iddingsite at these localities.

Hosking (1940) found that montmorillonite clay minerals are formed in the basalts of Australia where waterlogging of the soils is apparent, but under conditions of good drainage kaolinite is formed from basalts. In the lower part of the profiles in the Excelsior district not only would the required conditions of poor drainage be present, but also all the elements needed in the synthesis of nontronite (Noll, 1936; Ewell and Insley, 1935) would be available for the formation of nontronite from basaltic

glass, palagonite, iddingsite and augite. Most of the nontronite was formed from basaltic glass, some of which was changed to palagonite by the steam generated in the quenching of the lava. The partial alteration of the glassy groundmass of some basalts to nontronite, with the adjacent glass of the groundmass unchanged, indicates that the action of steam is not always necessary but that weathering under conditions of poor drainage in the presence of magnesium can completely change basaltic glass to nontronite. The change of basaltic glass to palagonite requires the removal of the same constituents as those removed in the change of most palagonites to nontronite. Where glassy fragments were converted to palagonite by the steam action, the tuffs composed of them were already started on the way to nontronite and weathering processes completed the action.

In the upper part of the profiles of weathering in the Columbia River region kaolinization of plagioclase feldspars started as soon as good drainage conditions were established and when the chemical system changed from alkaline to neutral or slightly acid. Migration or movement of clay minerals was favored by the conditions of good drainage (Allen, 1945) and the presence of dispersing agents. The clays with the highest alumina in the Excelsior district are composed of kaolinite or halloysite and contain notable additions of kaolinite that fills cracks and former vesicles in the basaltic rocks. Some of the kaolinitic clay in the cavities contains tiny muscovite flakes and grains of quartz that were transported from the sedimentary clays in the area into the openings. The remainder may have been derived from altered basalts at higher elevations. When streams cut downward into the nontronite zones, increased relief, and improved the conditions of drainage, nontronite migrated into vesicles and into cracks. The concentration of the nontronite in the veins at Excelsior, Colfax, Garfield and Manito was accomplished under these conditions. Later, some kaolinite was carried downward and filled veins that transect the nontronite veins at some localities. As conditions of thorough drainage penetrated progressively downward, neutral or slightly acid solutions invaded lower depths and kaolinization of plagioclase took place at levels where nontronite had formed early in the cycle. In Fig. 6 is illustrated a basaltic vitric tuff, in which palagonite has altered to nontronite, nontronite has migrated in veins and plagioclase has altered to kaolinite.

CONCLUSIONS

Nontronite in the Columbia River region was formed chiefly from basaltic glass and to a minor extent from iddingsite and augite. Palagonite is an intermediate step in the alteration that may be accomplished by the

steam generated in quenching of the lava. The partial alteration of the glassy groundmass of basalts to nontronite indicates that the action of steam is not always necessary but that weathering under conditions of poor drainage is essential to the genesis of nontronite.

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TWO OCCURRENCES OF CHLORITOID AS A HYDROTHERMAL MINERAL IN IGNEOUS ROCKS

J. K. GUSTAFSON, *Boulder, Colorado.*

ABSTRACT

Chloritoid occurs as a hydrothermal alteration mineral in pre-Cambrian lavas in the Porcupine district, Ontario, and Kalgoorlie district, Western Australia, and as a vein mineral in occasional quartz veins in the Porcupine district. These occurrences contradict geologic texts describing ottrelite and chloritoid solely as stress minerals resulting from the dynamic metamorphism of sedimentary rocks.

INTRODUCTION

The brittle micas chloritoid and ottrelite appear to be generally fixed in the geologic mind as stress minerals produced only in sedimentary rocks by dynamic metamorphism. For example, Dana's *Textbook of Mineralogy*, 4th edition (1),^a on pp. 667-668 describes the occurrence of these minerals thus, "Chloritoid (ottrelite, etc.) is characteristic of sedimentary rocks which have suffered dynamic metamorphism, especially in the earlier stages; it is thus found in phyllites, quartzites, mica schists, etc." Harker (2) and Grubenmann and Niggli (3) in their texts on metamorphism similarly discuss chloritoid only in connection with sedimentary rocks. Harker remarks (pp. 213-214), "The formation of chloritoid is probably dependent in the early stage of regional metamorphism upon the presence of kaolin." On page 149 he mentions, "other *distinctively stress-minerals** such as chloritoid, ottrelite, and staurolite." Winchell (4, p. 886) states that chloritoid occurs "only in crystalline schists where it may be abundant." This paper describes the occurrence of chloritoid as a hydrothermal alteration mineral in pre-Cambrian lavas at Porcupine, Ontario, and Kalgoorlie, Western Australia, and as a vein mineral in quartz-ankerite veins at the Hollinger mine in the Porcupine district.**

GEOLOGIC ENVIRONMENT OF CHLORITOID OCCURRENCES

The Porcupine and Kalgoorlie districts are among the most important gold mining districts in the world. Their geology is remarkably similar.

^a References are at the end of the paper.

* The italics are mine.

** This paper originated from observations made by the author in 1930-1932 while on L. C. Graton's staff during a study of the Hollinger Mine and during 1934-1936 while geologist for Western Mining Corporation Limited. The manuscript was written in 1937 and revised slightly in 1942. L. C. Graton suspected the hydrothermal origin of "chloritoid" in the Rand conglomerate (Hydrothermal origin of Rand gold deposits, p. 170, *Econ. Geol.*, 25, supplement, May 1930), and possibly other mining geologists have presented evidence elsewhere for the hydrothermal origin of chloritoid and ottrelite. Nevertheless a recent scanning of new texts on mineralogy suggests that this paper is still timely.

Porcupine District (5, 6)

The rocks of the Hollinger mine in which chloritoid is conspicuously developed are folded, sheared Keewatin lava flows ranging from albite dacite to albite andesite in composition. Fine-grained portions of the flows are frequently pillowed. All have been somewhat altered, and a number of distinct types of alteration can be recognized. The regional rock alteration that accompanied folding was slight. There was, however, a fairly widespread hydrothermal type of alteration that preceded vein emplacement and the development of alteration haloes around vein zones. This early alteration, where operative, generally turned the lavas of intermediate composition into ankeritic and sericitic or chloritic rocks. It also turned intrusive quartz porphyries into sericitic rocks and turned intrusive basic rocks into talcose or serpentine rocks.

The veins of the Hollinger mine are hypothermal gold-quartz veins containing subordinate carbonate, albite, tourmaline, and other minerals. The productive veins have strongly pyritized, sericitized, and ankeritized walls.

Kalgoorlie District (7, 8)

The foregoing description of the Porcupine rocks and of their metamorphism and hydrothermal alteration serves almost equally well for their Kalgoorlie counterparts. About the only modification required is that the pre-Cambrian lava flows in which the chloritoid is best developed at Kalgoorlie are basalts rather than andesites, and that the Kalgoorlie rocks include a thick diorite sill infolded with the flows.

The Kalgoorlie ore deposits, however, differ markedly from the Porcupine ore deposits. The primary Kalgoorlie ores are gold-pyrite-telluride replacement lodes occupying shear zones. Mineralogically they are somewhat similar to the Kirkland Lake ores of Ontario. Although generally classed as hydrothermal, they have many mesothermal characteristics.

CHLORITOID IN PORCUPINE DISTRICT

Chloritoid in Altered Lavas

In the eastern part of the Hollinger mine is an irregular pipe-like zone of extreme rock alteration. The zone is several hundred feet across and extends vertically downward for more than 4,000 feet. Within this zone the lava flows are strongly sericitized and ankeritized. Locally the rocks are flecked with small plates of chloritoid. Both pillow lavas and the coarser "greenstones" have been found to grade into the altered rock of this zone. Generally flow contacts can be traced through the zone with fair accuracy, and pillow outlines can often be recognized even where the

rock is thoroughly impregnated with ankerite, sericite, and chloritoid.

The microscope reveals a rock composed of 50% or more of ankerite. The remainder is chiefly a fine-grained crystallized quartz and sericite with subordinate chloritoid, chlorite, and occasionally a little pyrite.

The sericite appears in minute flakes scattered more or less randomly between ankerite and quartz grains or as wisps composed of parallel plates (up to 4 mm. in long diameter) which mark the schistosity. There is not the high degree of mineral parallelism suggestive of rock flowage that is found in true schists. Rather the textures suggest a later sericitization and ankeritization of a rock previously laminated by mechanical shearing.

Chloritoid occurs as small green plates (commonly 1 to 5 mm. across) which are readily detected in hand specimen. They are randomly oriented with regard to the rock cleavage. In thin section the plates appear to be rectangular with multiple twinning parallel to their length. The peculiar "hour-glass" pattern of the mineral is fairly common. The edges, especially the ends of the plates, are usually frayed, and the interiors of the plates are filled with inclusions of ankerite and occasionally quartz. These included grains are aligned in the plane of the rock cleavage, so that the schistose texture of the rock can be seen through the chloritoid grains. In several instances the mineral was concentrated about pyrite and tourmaline grains in intensely altered rock as if the mineral was recrystallized, if not introduced, at the time pyrite and tourmaline were formed. (Pyrite and tourmaline were clearly introduced by vein solutions.)

The following indices of refraction were obtained from one specimen: $\gamma = 1.724 \pm .003$, $\beta = 1.720 \pm .003$, $\alpha = 1.714 \pm .003$. These closely approximate the values for chloritoid. The other optical properties concur with those of either chloritoid or ottrelite.

Chloritoid in Quartz Veins

Some barren quartz-ankerite veins in the east end of the mine contain conspicuous quantities of chloritoid, only those veins, however, that occur within the previously described areas of chloritoid-bearing lavas.

The vein mineral chloritoid occurs in irregular patches several inches in diameter surrounded by quartz or as a narrow selvage separating quartz from wallrock. The patches probably represent replaced wallrock inclusions; the selvage may be the result of reaction between vein solutions and enclosing rock walls. Both patches and selvage consist of numerous rosettes of radiating chloritoid plates. Individual plates measure 2 mm. across.

The mineral possesses the following optical properties: optically (+); $\gamma = 1.723 \pm .003$, $\beta = 1.719 \pm .003$, $\alpha = 1.713 \pm .003$, $\gamma - \alpha = .010$; moder-

ately pleochroic, X=bluish green, Y=yellowish green, Z=greenish yellow; absorption $X=Y>Z$; $2V=55^{\circ}-65^{\circ}$ (visually approximated); Z makes an angle of $11^{\circ}\pm$ with a normal to (001). The mineral has a highly perfect basal cleavage (001) and probably a poor prismatic cleavage.

CHLORITOID IN KALGOORLIE DISTRICT

Chloritoid* is best developed in the altered pillow lavas of the "Older Greenstone" in the vicinity of Lake View Townsite on the east fringe of the "Golden Mile." Because of poor exposures, less is known about the shape and dimensions of this alteration zone than is known about the similar one at Porcupine. It is known, however, to be very local in its extent. Unoxidized rock from drill cores is indistinguishable to the naked eye from similar chloritoid-bearing rock from the Hollinger mine. The lava flows within the Kalgoorlie alteration zone have also been heavily impregnated with ankerite and sericite and flecked with chloritoid. I did not study the Kalgoorlie chloritoid rock microscopically. I do not doubt however, that the Porcupine rock and the Kalgoorlie rock are similar both as to composition and origin.

CONCLUSIONS

The occurrence of chloritoid as a vein mineral and as a product of hydrothermal alteration in lavas makes it necessary to revise the common impression that chloritoid is a stress mineral, that it is necessarily indicative of dynamic metamorphism, and that it forms only in altered sediments.

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* The mineral might be ottrelite. Stillwell (8) refers to it as chloritoid although on Finucane's map accompanying Stillwell's bulletin, the mineral is indicated as ottrelite.

NOTES AND NEWS

MEASUREMENT OF THE ALPHA INDEX OF REFRACTION IN MICACEOUS MINERALS*

MARIE LOUISE LINDBERG,

U. S. Geological Survey, Washington, D. C.

The determination of the three indices of refraction of micaceous minerals by the immersion method presents difficulties for the index normal to the plates. Several methods have been proposed. Ferguson and Peacock¹ have outlined a method for determining the alpha index of refraction in micaceous minerals, using the universal stage. In many laboratories the required orientation in minerals with perfect cleavage is obtained by manipulating the cleavage grains against fragments of crushed glass. Ferguson and Peacock have pointed out an objection applicable to this method: "The measurement of the refractive index for the third principal direction, which is nearly normal to the cleavage, is difficult, since it involves setting the plate on edge, and it is not likely to be very accurate, since the conditions are unfavorable for the Becke effect, and the observations may have to be made very rapidly while the plate moves through an upright position." Solid immersion media such as those described by Merwin² are used to obtain the optical properties of minerals which have excellent cleavage. This method requires a set of the calibrated solid media. Fairbairn³ has called attention to the method of Vedeneeva⁴ for fixing the position of grains on a gelatin-coated slide.

In this paper a procedure to orient grains is presented so that the alpha index of refraction of micaceous minerals may be measured. The underlying principle is that grains falling at random on a viscous adhesive surface will maintain their position. The alpha index of refraction of micas may then be measured on those grains which stand vertically. The

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¹ Ferguson, R. B., and Peacock, M. A., Measurement of the three principal indices of refraction in micaceous minerals by immersion on a tilting stage: *Am. Mineral.*, **28**, 563-570 (1943).

² Merwin, H. E., Media of high refraction for refractive index determination with the microscope; also a permanent standard media for low refraction: *Jour. Wash. Acad. Sci.*, **3**, 35-40 (1913).

³ Fairbairn, H. W., Gelatin coated slides for refractive index immersion mounts: *Am. Mineral.*, **28**, 396-397 (1943).

⁴ Vedeneeva, N., and Melancholin, N., The theodolite immersion method., etc.: *Trans. Sci. Invest. Inst. Industry*, No. 503. *Inst. App. Miner.*, Paper 54 (1932), (Russian and English).

mounting medium must be immiscible with the index oil, in order that the index of refraction of the oil will not be changed while in contact with the mounting medium. Canada balsam, though viscous, is not a suitable medium as it slowly dissolves in the index oils. Water glass does not present this difficulty as it is immiscible with the index oils. The method described here involves spreading mineral particles on viscous water glass, adding index oils and cover glass, and measuring the indices on grains oriented according to the following procedure.

A drop of water glass⁵ from the end of a stirring rod is placed in the center of a glass slide. Slides with a shallow well are convenient. The water glass is stirred to prevent a skin from forming on the surface, as it becomes more viscous. At first the water glass will flow back into the path of the stirring rod. The water glass is then too fluid, and a mineral grain dropped on its surface will lie flat. Stirring is continued until the water glass no longer fills in the path of the stirring rod. It is then allowed to set for half a minute. Fine-grained particles of the mineral are then sprinkled on the surface, and the mount is allowed to set for a minute.

If a cover glass were placed directly on the mineral grains, its weight would flatten the grains. A small ring made from a piece of copper wire is therefore used as a suitable support for the cover glass. A wire with a diameter of 1 mm. is curved into a loop, and flattened with a hammer to a third of its thickness and with an inside diameter of about 11 mm., which is slightly less than the diameter of the cover glass. This ring is placed around the water glass and mineral grains. If a glass slide with a shallow well is used, the ring should be approximately the same size as the well. The desired index oil is placed over the grains, and a cover glass with a diameter of 12 mm. is drawn over the wire from one side. If enough oil has been added to fill the ring, bubbles will not form.

The number of micaceous grains standing on end is influenced by the degree of crowding and grain size. A fraction of a per cent to about three per cent may stand upright.

The more crowded the grains are the greater are the chances that a given grain will stand upright. However, with many grains crowded together, conditions are not favorable for measurement of the index of refraction by the Becke line method. The edge of one upright grain should not be obscured by another grain. A little practice will show how much crowding can be permitted in order to obtain a maximum number of upright grains without interfering with the observation of the Becke line.

A second factor upon which the number of grains standing on end

⁵ Commercial water glasses vary in their strength. The author has used successfully sodium silicate, 40° Bé solution, obtained from the Baker Chemical Co.

depends is grain size. In the various mesh sizes, 65–100, 100–150, and 150–200, the coarsest grains contained the least upright grains; the intermediate sized grains had more; the smallest grains had the most. The lower edge of a mica plate embedded in the water glass will support a small grain standing upright more easily than a large grain.

The water glass in which the mineral grains are partly set does not affect the values obtained for the index of refraction. The Becke line effect depends upon a vertical contact surface between the mineral and the oil.

Since the cleavage of micaceous minerals is perfect in one direction only, in directions perpendicular to this cleavage, mica breaks with a hackly fracture. A cross section through the short direction of the upright mica plate appears under the microscope like a saw tooth edge and it is difficult to tell in which direction the Becke line is moving, because of the proximity of nearby cleavage pieces. It is easier to measure the α index of refraction at the corner of the upright plate than along the length of the plate, as the hackly fracture does not interfere here.

In order to check the accuracy of the procedure given above, the indices of refraction of several micas already determined by others were measured. Comparison of results are given below:

TAENIOLITE FROM MAGNET COVE, ARKANSAS

	C. S. Ross ⁶	M. L. Lindberg
α	1.522	1.524
β	1.553	1.554
γ	1.553	1.554

CESIUM BIOTITE FROM CUSTER COUNTY, SOUTH DAKOTA

	J. J. Fahey ⁷	M. L. Lindberg
α	1.573	1.573
β	1.620	1.621
γ	1.620	1.621

LEPIDOLITE, WESTERN AUSTRALIA, STEVENS No. 14

	M. E. Jefferson ⁸	M. L. Lindberg
α	1.525	1.526
β	—	1.559
γ	1.558	1.559

⁶ Miser, H. D., and Stevens, R. E., Taeniolite from Magnet Cove, Arkansas: *Am. Mineral.*, **23**, 106 (1938).

⁷ Hess, Frank L., and Fahey, J. J., Cesium biotite from Custer Co., South Dakota: *Am. Mineral.*, **17**, 175 (1932).

⁸ Hendricks, Sterling B., and Jefferson, Merrill E., Polymorphism of the micas, with optical measurements: *Am. Mineral.*, **24**, 760 (1939).

LEPIDOLITE, RAMONA, CALIFORNIA, STEVENS No. 15

	M. E. Jefferson ⁹	M. L. Lindberg
α	1.533	1.532
β	—	1.550
γ	1.555	1.554

⁹ *Ibid.*, p. 758.

AN OCCURRENCE OF PYROMORPHITE IN ILLINOIS

ROBERT M. GROGAN, *Illinois State Geological Survey*.*

Pyromorphite has been identified in a lead ore concentrate from the Alco Lead Company mine in the fluorspar-lead-zinc district of southern Illinois. This mineral has not previously been reported from southern Illinois despite the relatively common occurrence of galena in the ore and the considerable oxidation of parts of some deposits. Failure to recognize the mineral earlier may be due to its scarcity, an inconspicuous mode of occurrence, or insufficient opportunities for a geological examination of the weathered portions of deposits.

The mineral, however, has been reported from the fluorspar district of western Kentucky by W. S. Tangier Smith,¹ who states that pyromorphite "occurs in minute or microscopic green translucent crystals, as individuals or small aggregates. It is comparatively rare, but was noted in small amount on fluorite at the Tabor and Wheeler mines and in druses in a cavity once occupied by galena at the Kentucky No. 4 shaft."

Occurrence

The lead ore containing the pyromorphite came from the open-pit Patrick mine of the Alco Lead Company in the SW $\frac{1}{4}$, NW $\frac{1}{4}$, NW $\frac{1}{4}$, sec. 16, T. 12 S., R. 9 E., Hardin County, about 8 miles northeast of Rosiclare. The presence of an unusual mineral in the ore was indicated by the appearance of a broad fringe of green material at the upper margin of the lead concentrate on a Deister table in the company's mill. A sample of the green material was sent to the State Geological Survey by Mr. W. L. Skinner, Superintendent, in May 1945 and identified as pyromorphite. Later the writer visited the mill and observed a few minute grains of pyromorphite in the finer-grained Deister table concentrates, but was unable to find the mineral in place in the ore deposit. There can

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¹ Ulrich, E. O., and Tangier Smith, W. S., The lead, zinc, and fluorspar deposits of western Kentucky: *U. S. Geol. Survey, Prof. Paper* 36, 122 (1905).

be no doubt, however, that the mineral observed on the concentrating tables came from the Patrick mine.

The ore at the Patrick mine is principally a mixture of galena, cerussite, and anglesite in a gangue of red-brown clay and weathered silicified limestone. A small amount of fluorspar is occasionally observed in the ore. The deposit occurs from 15 to at least 50 feet below the surface, and apparently has been produced by the weathering of a primary deposit of galena along a minor fracture zone in cherty Fredonia limestone (Mississippian).

Identification

Examination of the sample of ore concentrate with the binocular microscope showed that about one-fourth of the mineral grains were colored various shades of green, and that most of the other grains were light gray to pinkish gray in color and subsequently identified as cerussite. Rough fragments of chert and crystal fragments of galena, quartz, and anglesite were observed in minor amounts. Practically all of the grains were less than 100-mesh in size, and many passed a 200 mesh sieve.

An essentially complete separation of the pyromorphite from the cerussite was accomplished by taking advantage of the differential solubility of the two minerals in cool dilute nitric acid.²

The quartz and chert which survived the acid treatment were removed by a bromoform separation. The resulting concentrate was estimated to contain over 95 per cent pyromorphite and less than 5 per cent impurities, chief among which were galena and anglesite. The specific gravity of this concentrate was 6.87 as determined with a micropycnometer.³

Many of the pyromorphite grains are minute prismatic hexagonal crystals, others are rounded. Their color ranges from pale yellowish green to strong bluish green. The crystals are uniaxial and optically negative, and are length-fast. In ordinary light ω is approximately 2.058 and ϵ somewhat less, but greater than 2.035. The birefringence appears to be slightly greater than that of quartz. The more strongly colored crystals are weakly pleochroic with X = colorless to pale yellow-green, Z = stronger yellow-green or blue-green.

The x-ray diffraction pattern obtained by the powder method is un-

² A portion of the original sample was gently heated in concentrated nitric acid and then rapidly diluted with cold distilled water, whereupon the cerussite dissolved with vigorous effervescence. Quick decantation of the acid followed by immediate washing with distilled water preserved most of the pyromorphite for further study.

³ Clark, H. S., Micro-analyst, Illinois State Geological Survey, personal communication.

mistakably that of pyromorphite.⁴ Chemical tests on the pyromorphite concentrate from the bromoform separation showed the presence of abundant chlorine and phosphorus, and the absence of vanadium and arsenic,⁵ thus eliminating the possibility of the presence of the closely related minerals, vanadinite or mimetite.

⁴ Bradley, W. F., x-Ray Technologist, Illinois State Geological Survey, personal communication.

⁵ McVicker, L. D., Analyst, Illinois State Geological Survey, personal communication.

RUTILE IN HARFORD COUNTY, MARYLAND

W. HAROLD TOMLINSON, *Springfield, Pennsylvania.*

On the geological map of Harford County, published by the Maryland Geological Survey, there is shown a narrow belt of serpentine rocks starting from a point about a mile northwest of Pylesville and extending about five miles in a direction south of west. The ultrabasics are intruded into Wissahickon schist. On the north side of this belt, in a field on the east side of the road, a mile north of Clermont Mills, several prospect pits have been opened for rutile.

The formation carrying the rutile is a chlorite rock, probably an altered pyroxenite. It has a slightly schistose structure, much more noticeable in some of the samples collected than in others, but always sufficiently strong to indicate a shearing movement during metamorphism. Little can be learned from the meager outcrop as to the extent of the rutile-bearing formation. A porous talc rock was found in place just east of the pits and again as float southeast of the pits. North of the pits chloritic schist carrying a little rutile is exposed. Except for a few weathered samples found in place, the material examined was collected from the dump of the main pit.

The only mineral that can be considered as a main constituent of the rock is a chlorite with positive optical sign, β index 1.589, birefringence about .008, and weak dispersion. The accessory minerals are magnetite, rutile, apatite, ilmenite, talc, biotite, pyrite and zircon. The first seven of these are distributed unevenly or in pockets. The zircon, which constitutes only a fractional percentage of the rock is rather evenly distributed. It occurs in small and crushed crystals and is probably an original mineral that has remained unchanged during metamorphism.

Of the accessory minerals, magnetite is most abundant. It occurs in well developed octahedrons up to 6 mm. in diameter. These are sparsely distributed all through the formation but are abundant in pockets. No trace of titanium could be found in the mineral. In this district magnetite

is a common constituent of chloritic schists of igneous origin which contain little or no rutile and it seems probable that the mineral here has been derived from the alteration of the pyroxene.

The second most abundant accessory mineral is rutile. The mineral shows no unusual physical or optical properties.

TABLE 1. SPECTROGRAPHIC ANALYSIS MADE BY THE JOHN HERMAN LABORATORIES, LOS ANGELES

Analysis of a surface altered sample collected in place north of pits. A thin section showed ilmenite altering to rutile in a rock composed of chlorite, biotite, and traces of osteolite.

	<i>Elements</i>	<i>Probable Distribution</i>
% 10. plus.....	Silicon	Chlorite, biotite
1. -10.....	Magnesium	Chlorite, biotite
	Iron	Chlorite, oxides
	Aluminum	Chlorite, biotite
	Titanium	Rutile, ilmenite
.1 - 1.....	Potassium	Biotite
	Manganese	Ilmenite
	Sodium	Biotite
	Calcium	Osteolite
.01 - .1.....	Barium	
	Nickel	Sulfides
	Vanadium	Rutile
	Tin	Rutile (?)
	Copper	Sulfides
	Zinc	Sulfides
	Cobalt	Sulfides
.001 - .01.....	Boron	
	Chromium	Rutile
.0001.....	Silver	Sulfides

Analysis of selected rutile crystals. Examination with lens showed traces of apatite and chlorite adhering to the crystals selected.

	<i>Elements</i>	<i>Probable Distribution</i>
% 10. plus.....	Titanium	Rutile
1. -10.....	Iron	Rutile, chlorite
	Silicon	Chlorite
.1 - 1.....	Aluminum	Chlorite
	Magnesium	Chlorite
.01 - .1.....	Calcium	Apatite
	Boron	
.001 - .01.....	Vanadium	Rutile
	Lead	
	Tungsten	
	Nickel	
	Manganese	Rutile
.0001- .001.....	Gold	
	Copper	

A spectrographic analysis made by the John Herman Laboratories of Los Angeles, shows the presence of small quantities of vanadium, tin, chromium, manganese and tungsten. No quantitative chemical analysis is available. The rutile is mostly euhedral in form and occurs in sagenitic groups distributed in pockets through the chlorite rock. In pockets in which it is associated with apatite, the crystals are stouter and the geniculated twinning is not so well developed (Fig. 1). The largest crystal found measured 25×6 mm. Pockets carry up to 16% rutile with an average content of 8%. Samples collected from the outcrops north and east of the pits show ilmenite in process of alteration to rutile. It seems likely that all these rutile-bearing pockets represent alteration of pockets of ilmenite originally present in the pyroxenite.

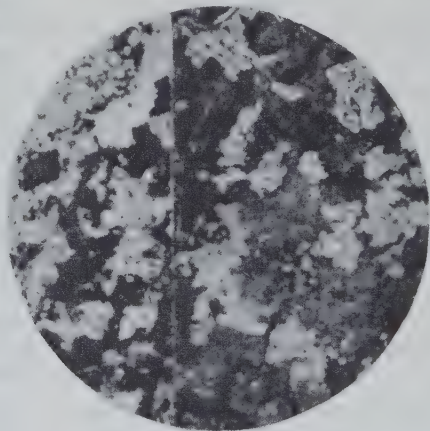


FIG. 1. (Right). Sagenitic rutile in chlorite rock. Light gray, rutile; medium gray, magnetite; black with lustre, chlorite. (Left). Rutile in pocket with apatite. White is apatite. Photo of polished slabs about $\frac{2}{3}$ natural size.

The apatite, white in color, occurs in irregular masses of granular texture and occasionally in rough euhedral crystals. The mineral usually shows effects of crushing. It is very unevenly distributed and is found always in pockets in which it forms a high percentage of the rock. Its indices, $\epsilon = 1.644$, $\omega = 1.648$ are too high for pure fluorapatite and suggest the presence of chlorine. It seems probable that apatite was an original mineral in the pyroxenite and was crushed and recrystallized during metamorphism.

Veins of pure white talc 3 mm. to 5 mm. wide were found cutting the chlorite rock. Biotite was found in pockets in some of the samples. It occurs in well developed crystals of light yellow color and shows no sign of alteration. In a thin section the mineral is colorless with no noticeable pleochroism. The beta index, 1.61, suggests a biotite low in iron.

A few scattered crystals of pyrite were found in some samples but the mineral is very sparsely distributed. It may be an original constituent of the pyroxenite.

Ilmenite was found in specimens collected from the outcrops. North of the pits it was found in small platy crystals disseminated through the chlorite in association with magnetite. Most of the crystals show incipient alteration to rutile. East of the pits ilmenite was found showing an advanced stage of alteration to rutile. It seems probable that ilmenite was an original mineral of the pyroxenite.

Origin of the Formation

There are in the vicinity of this rutile-bearing formation, large bodies of hypersthene gabbro which grade into pyroxenite. Ilmenite occurs in the gabbro and has been reported as locally abundant in the pyroxenite. Apatite also occurs in the gabbro and has been reported as forming, in pockets, as much as 12% of the rock (Mt. Hope Station).

It seems probable that this rutile-bearing formation represents a pyroxenite originally rich in ilmenite and apatite which has separated from the gabbro and which has been altered, first by deuteric action, to an amphibolite rich in ilmenite and apatite, and later, during regional metamorphism, to a chlorite rock rich in rutile and apatite.

At the amphibolite stage of its metamorphism the rock would correspond in its mineral composition to a hornblende nelsonite as described by Thos. L. Watson (*Bull.* 111A, *Va. Geol. Surv.*).

The Harford County rock differs from hornblende nelsonite as described by Dr. Watson in that it contains euhedral rutile in place of ilmenite and chlorite in place of hornblende. The writer would therefore classify the formation as a regionally altered hornblende nelsonite.

SUPPOSED TROILITE FROM LLALLAGUA, BOLIVIA, IS PROBABLY TETRADYMITÉ

In the recently published Mineralogy of the Tin Mines of Cerro de Llallagua, Bolivia (*Proc. Acad. Nat. Sci. Phila.* **XCVI**, 308-310, and Fig. 18), several minute crystals found in tiny vugs in the porphyry adjacent to a vein were identified as troilite on the basis of the closeness of the angular measurements of the crystals to recorded data of Rose for pyrrhotite from a meteorite.

The writer is indebted to Professor Martin J. Brueger for a reëxamination of the crystals. He discovered them to be plastic: a crystal could be smeared into tiny flakes, with curling of the basal plane. To quote from his letter "Since pyrrhotite is known to be non-plastic, I am sure that the crystals you sent me are not troilite, but rather something tetradymite-like. This opinion is reinforced by the rhombohedral habit of the crystals."

Another inexcusable error occurred on page 281, where the reference to the synthesis of cassiterite by Daubréé in 1849 "(the first synthesis of a mineral!)" should have been a more correct quotation from Clarke's Data of Geochemistry as the first synthesis of the mineral.

SAMUEL G. GORDON,

The Academy of Natural Sciences of Philadelphia

PROCEEDINGS OF SOCIETIES

PHILADELPHIA MINERALOGICAL SOCIETY

The Academy of Natural Sciences of Philadelphia, September 6, 1945

The vice-president, Mr. Charles R. Toothaker, presided—with 53 persons present. Summer trips were reported by Mr. Cochrane to New Mexico and Arizona, by Paul Seel to Sayresville (pyrite in the clay pits), by Mr. Flack to the Cornog quarry (blue quartz and epidote), and by Messrs. Gordon and Hesse to the coal strippings north of Pottsville (quartz crystals and dickite).

A. ROSENZWEIG, *Sec. pro tem.*

October 4, 1945

Dr. W. Hersey Thomas was in the chair, with 64 persons present. The following officers were elected: President, Dr. W. Hersey Thomas; Vice-President, Charles R. Toothaker; Secretary, Charles A. Belz; Treasurer, Harry W. Trudell; Councillor: Robert Hesse.

Dr. S. J. Shand of Columbia University addressed the society on "Chemical Equations Preserved in Stone." The title of the address was borrowed from J. J. Sederholm, who thus described the remarkable coronas which occur in some gabbroic rocks. These coronas preserve various stages of reaction between olivine (less commonly iron ore) and plagioclase. The structure of coronas was described and illustrated with lantern slides, and the conditions of their formation were discussed. The speaker stated that coronas are produced by thermal metamorphism of rocks of suitable mineralogical composition. He next considered the equation which expresses the desilication of albite by reaction with dolomite to produce nepheline, as required by Daly's hypothesis for the formation of the alkaline rocks. This too is a "chemical equation preserved in stone," although in this case the evidence is not to be seen under the microscope, but in the field. The case for Daly's hypothesis was supported by lantern slides of geological maps and sections.

Mr. Charles A. Thomas exhibited a pumiceous slag which was formed by fusion of the sand about the crater produced by the atomic bomb test at Alamogordo, New Mexico.

November 1, 1945

Dr. W. Hersey Thomas presided, with 72 present.

Mr. Nicola Goodwin D'Ascenzo spoke on "Asterism," and illustrated his address by specimens from his collection, and by lantern slides. He also awarded 5 prizes to those who had identified gemstones among the 45 he had placed on exhibition in the Academy.

December 6, 1945

Dr. Thomas was in the chair, with 66 persons present. Mr. Louis Moyd spoke on "Exploration of Mineral Deposits," in which various phases such as mapping, sampling, and drill-coring were illustrated by maps and photographs. Areas described included the nepheline syenite and corundum and graphite deposits in Ontario, the Yellowknife area, and Great Bear Lake.

CHARLES A. BELZ, *Secretary*

NEW YORK MINERALOGICAL CLUB, INC.

Abstract of meeting of March 20, 1946

A nominating committee was chosen to nominate the officers for the coming year. Dr. Pough and Dr. Hawkins are compiling data for a publication on the mineral localities around New York City. Dr. Kerr, the speaker of the evening spoke on "A Recent Mineralogical Reconnaissance" referring to the problems of wall rock alterations in (1) a sericite deposit in Nevada, (2) at Butte, Montana and (3) at the Tintic District, Utah.

MRS. E. J. MARCIN, *Secretary*

NEW MINERAL NAMES

Franquenite

RENÉ VAN TASSEL, Occurrence de minéraux sulfatés récents sur des schists de Mousty, à Frankenies. *Bull. Mus. Hist. Nat. Belgique*, 20, No. 16, 24 pp. (1944); through *Mineralog. Abstracts*, 9, 125 (1945).

"Yellow efflorescences (previously thought to be sulfur) on Cambrian shales consist mainly of a new species named franquenite. Minute hexagonal scales (8–15 μ across, 2 μ thick) have $n_O = 1.531$, $n_E = 1.494$, $G. = 1.87$ – 1.94 . Analysis gave SO_3 32.77, Al_2O_3 5.51, Fe_2O_3 14.84, FeO 1.00, MgO 4.23, alkalis not detd., H_2O 40.69; sum 99.04 per cent. From this the formula $(Mg, Fe)_2(Fe, Al)_6(SO_4)_3(OH)_6 \cdot 41H_2O$ is derived. It is slowly soluble in cold water. A dehydration curve is given; 28.2 per cent H_2O is lost at 110°. This new mineral is compared with slavikite."

DISCUSSION: The analysis does not lead to the formula as given above, but gives approximately $(Mg, Fe)O : (Al, Fe)_2O_3 : SO_3 : H_2O = 2 : 1.5 : 8 : 40$ –45. The most recent analysis of slavikite (Gordon, 1941) gave $MgO : Fe_2O_3 : SO_3 : H_2O = 2 : 1 : 8 : 39$. Gordon reported $n_O = 1.533$, $n_E = 1.497$, $G. = 1.99$, for rhombohedral slavikite.

In view of these correspondences, there seems to be no justification for this new name.

MICHAEL FLEISCHER

Tschermakite

A. N. WINCHELL: *Am. Mineral.* 30, 29 (1945).

Ferrotschermakite

A. N. WINCHELL: *Am. Mineral.*, 30, 29 (1945).

Groutite

J. W. GRUNER: *Am. Mineral.*, 30, 169 (1945) (abs.).

Cattierite

PAUL F. KERR: *Am. Mineral.*, 30, 483–497 (1945).

Vaesite

PAUL F. KERR: *Am. Mineral.*, 30, 483–497 (1945).

Brazilianite

F. H. POUGH AND E. P. HENDERSON: *Am. Mineral.*, 30, 572–582 (1945).

DISCUSSION: The nomenclature proposed by Kerr for the system FeS_2 – NiS_2 – CoS_2 seems more complex than is warranted in view of the rarity of NiS_2 and CoS_2 . It would have been simpler to redefine bravoite as in the Seventh Edition of *Dana's System*, thus avoiding the introduction of the new name vaesite.

M.F.

BOOKS—WAR VICTIMS

During the war, the libraries of half the world were destroyed in the fires of battle and in the fires of hate and fanaticism. Where they were spared physical damage, they were impoverished by isolation. There is an urgent need—now—for the printed materials which are basic to the reconstruction of devastated areas and which can help to remove the intellectual blackout of Europe and the Orient.

There is need for a pooling of resources, for coordinated action in order that the devastated libraries of the world may be restocked as far as possible with needed American publications. The American Book Center for War Devastated Libraries, Inc. has come into being to meet this need. It is a program that is born of the combined interests of library and educational organizations, of government agencies, and of many other official and non-official bodies in the United States.

The American Book Center is collecting and is shipping abroad scholarly books and periodicals which will be useful in research and necessary in the physical, economic, social and industrial rehabilitation and reconstruction of Europe and the Far East.

The Center cannot purchase books and periodicals; it must depend upon gifts from individuals, institutions, and organizations. Each state will be organized to participate in the program through the leadership of a state chairman. Other chairmen will organize interest in the principal subject fields. Cooperation with these leaders or direct individual contributions are welcomed.

WHAT IS NEEDED: Shipping facilities are precious and demand that all materials be carefully selected. Emphasis is placed upon publications issued during the past decade, upon scholarly books which are important contributions to their fields, upon periodicals (even incomplete volumes) of significance, upon fiction and non-fiction of distinction. All subjects—history, the social sciences, music, fine arts, literature, and especially the sciences and technologies—are wanted.

WHAT IS NOT NEEDED: Textbooks, out-dated monographs, recreational reading, books for children and young people, light fiction, materials of purely local interest, popular magazines such as *Time*, *Life*, *National Geographic*, etc., popular non-fiction of little enduring significance such as Gunther's *Inside Europe*, Haliburton's *Royal Road to Romance*, etc. Only carefully selected federal and local documents are needed, and donors are requested to write directly to the Center with regard to specific documents.

HOW TO SHIP: All shipments should be sent *PREPAID* via the cheapest means of transportation to *THE AMERICAN BOOK CENTER, C/O THE LIBRARY OF CONGRESS, WASHINGTON 25, D. C.* Although the Center hopes that donors will assume the costs of transportation of their materials to Washington, when this is not possible reimbursement will be made upon notification by card or letter of the amount due. **THE CENTER CANNOT ACCEPT MATERIAL WHICH IS SENT COLLECT.** Reimbursement cannot be made for packing or other charges beyond actual transportation. When possible, periodicals should be tied together by volume. It will be helpful if missing issues are noted on incomplete volumes.

K. R. SHAFFER, *Executive Director,*
American Book Center, Inc.,
Library of Congress, Washington 25, D. C.